Aalto University
School of Engineering

Pablo López Trabalón

Experimental study on the drying kinetics of wood veneer in a contact drying

Master's thesis for the degree of Master of Science in Technology submitted for inspection.

Espoo, 30.06.2020

Supervisor: Sanna Syri

Advisor(s): Timo Laukkanen and Henrik Holmberg

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Pablo López Trabalón

Title of thesis Experimental study on the drying kinetics of wood veneer in contact drying

Master programme Energy Technology **Code** EEN

Thesis supervisor Sanna Syri

Thesis advisor(s) Timo Laukkanen; Henrik Holmberg

Date 30.06.2020 **Number of pages** 48 **Language** English

Abstract

Concerning environmental protection, we should reduce as much as possible the use of non-renewable resources and consume efficiently the renewable resources that we have. Plywood, as an engineered product, offers great opportunities to perform efficiently veneer based products from wood, which is one of the most important renewable sources. In the plywood process, the drying consumes a lot of energy. Therefore, any improvements in drying-process efficiency result in significant overall energy savings. Contact drying is an alternative technology to convective drying that is the most used in this sector due to its large industrial capacity. However, contact drying usually has better energy efficiency because the heat is directly transferred into material by conduction.
This master's thesis focuses on the experimental study of a contact dryer, which is equipped with a vacuum pump to work under atmospheric pressure. Although the thesis work is divided into three blocks: the so-called drying curves, energy consumption and modelling of drying time, the main goal is experimentally defining drying times of veneers with various thickness at different work conditions. The result of these measurements are drying curves, but drying time is the wanted parameter.
The most relevant factors that affect drying are the temperature of the heated plate, the pressure inside the drying box and veneer thickness. The effect of these factors is studied by measuring the drying curves that show the moisture-content behaviour in relation to drying time, helping us to understand how they influence drying process.
A drying-time model is proposed to describe the veneer drying using the laboratory contact dryer. The modelling is the product of a thermodynamic analysis between the dryer and the veneer. Modelled and experimental time are compared, and the variations between them are analysed.
In addition, an experimental study of energy consumption is exposed, which is useful to understand better the dryer behaviour when it is taking water out of veneers. This point in combination with the analysis of drying curves let known the fundamental aspects of contact drying for wood veneers.

Keywords dying time; moisture content; modelled time; energy consumption

Index

List of Tables

List of Figures

1 Plywood in Finland and the manufacturing process

Finland is the biggest producer of plywood and veneer sheets in the EU and the history of this industry is over one hundred years old with an important contribution to the gross domestic product and the national economy. [1]

The total estimated production of plywood in 2018 was 1.23 million m^3 and the exported share of that was 1.01 million m^3 [2]. The plywood products are usually used as components in furniture and in transportation applications. Besides, there are many specialised applications such as aerospace or boat building where the quality of the plywood is crucial.

Plywood-board production is based on laminating veneers jointly. The process begins with the selection of raw materials that will depend on the intended application. Once the materials (logs) have been delivered to the manufacturer, the first step is conditioning them. This process involves heating logs by steam or hot water performing the required temperature to facilitate debarking and softening of the material for the next step, veneer peeling.

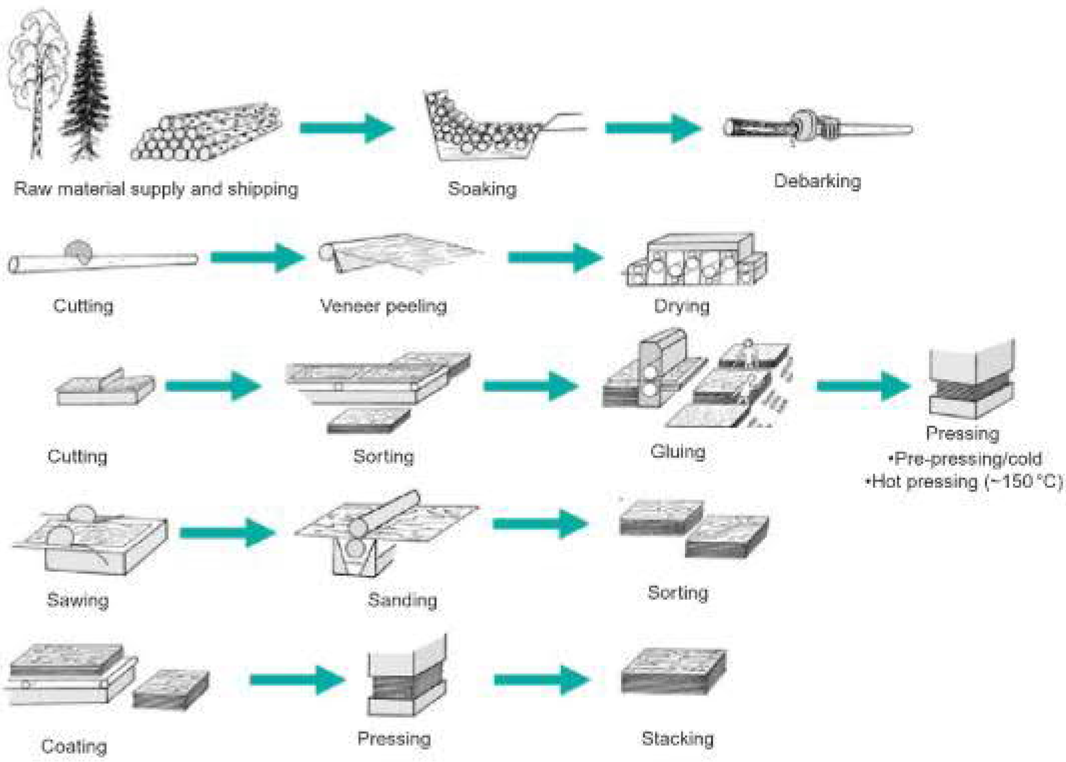


Figure 1. Schematic plywood manufacturing process in Nordic Countries [3]

Once the log is cut longitudinally to fill it into the peeling lathe, veneer is produced by rotatory peeling, which is the most common process, although there are other alternatives to reach specialised products.

After peeling and before drying, the veneers are checked to find any irregular features and sorted to pool the same type of veneers that will be dried together.

Direct convective drying is the principal technology used in industrial veneer drying, although alternative drying methods are in development such as contact drying, which is matter of this thesis. This method reduces considerably both drying time and overall energy savings that is very important since the drying process is energy-intensive, taking around 70% of the thermal energy used by the whole manufacturing process and it consumes up to 60% of the total energy consumed. [3]

After drying the veneers, they are cooled and tested to classify them according their properties and moisture content since a very important point in the plywood production is to maximise the yield of proper veneer that becomes part of the product. Then, veneer sheets are created by join and cut to the desired dimensions. Machine vision is used to detect any defect on the sheet, and in case of finding anything, it is repaired by replacing the defected portion with a veneer patch free of defects. [3]

The most used synthetic glue to bond wood veneer is Phenol formaldehyde, a thermosetting resin which requires heat and pressure for a proper gluing. This resin is characterised by exceptionally strength, water, and thermal resistance, especially those products destined to exterior applications. Since formaldehyde is classified as human carcinogen, formaldehyde-free resins are increasing their use, but mainly for interior applications. [3]

The formation of plywood is based on plies of bonded veneers laid up orthogonally and alternatively with an uneven number of plies, where the grain direction of the surface plies have the same direction, and the structure is symmetrical about the mid-plane, creating a balanced structure. After glue application and waiting some time to allow the penetration of the glue, the glued veneers are pre-pressed to begin the consolidation process. Then, the product is hot-pressed forming the consolidate plywood. In the case of Phenol formaldehyde resin, the press plates are heated approximately to 130°C. Parameters such as press pressure and duration of pressing are carefully controlled to ensure the required panel-thickness. [3]

Finally, the reached product is cut to the desired dimensions and if there are no defects, the plywood is sanded and graded for its commercialization. [3]

2 Plywood properties and applications

Plywood is composed of plies that can be performed by different materials depending on the purpose of its application. Regarding the standards of Finnish plywood, that are based on the European Standard EN 635, there are four constructions:

- Birch: birch veneers for all the layer construction.
- Combi: two birch veneers on each face and alternate plies of conifer and birch veneers for the core plywood.
- Combi mirror: one birch veneer on each face and alternate plies of conifer and birch veneers for the core plywood.
- Conifer: conifer veneers for all the layer construction. Spruce or occasionally pine on each face.

These constructions are graded according to the presence of defects such as knots, holes, splits, and discolouration on their face veneers.

The plywood constructions can be also coated to get specific properties. The main types of surfaced panels manufactured by Finnish plywood industry are phenolic, painting, melamine film faced and a wide variety of other special products. Other available technologies, applied to plywood, are scarf jointed to get maxi size panels and CNC (Computer Numerical Control) technology to drill, profile and machine the product. [4]

2.1 Mechanical properties

The mechanical properties of plywood are linked to the raw material and the structure of the product. Wood, as well as a simple veneer, is highly anisotropy.

The strength properties vary depending on longitudinal or orthogonal direction. For this reason, veneers are joint and glued alternating both crosswise directions where the high longitudinal strength and stiffness of the veneer mitigate the much lower properties of its adjoining one. This balanced structure ensures a suitable behaviour when it suffers loading, or changes in its moisture content (also highly anisotropic).

Therefore, the degree of plywood anisotropy is significantly lower than the degree of its raw wood, and it can be reduced as many times as the number of veneers increases. This multi-ply structure is always composed of uneven number of veneers. For example, the number of plies for Birch plywood can range from 3 to 35. [3],[4]

Mechanical properties are the most used to evaluate wood-based composites, such as plywood, for structural and non-structural applications. Elastic and strength properties are useful to establish design or product specifications. Elastic properties include modulus of elasticity in bending or Flexural modulus, tension, and compression. Strength properties include modulus of rupture (bending strength), compression strength, tension strength, shear strength, fastener holding capacity, and hardness. The characteristics values for plywood-properties are listed below in Table 1 and Table 2 (same table divided in two parts).

Table 1. Mechanical properties of plywood (I) [5]

Mechanical Properties	*METRIC*	*COMMENTS*
Tensile strength	27.6 - 34.5 MPa	Parallel to face
Modulus of rupture	0.0483 - 0.0689 GPa	Parallel to face
Flexural modulus	8.20 - 10.3 GPa	Parallel to face

Table 2. Mechanical properties of plywood (II) [5]

Mechanical Properties	*METRIC*	*COMMENTS*
Compressive strength	31.0 - 41.4 MPa	Parallel to face
Shear Modulus I	0.138 - 0.207 GPa	In plane
Shear Modulus II	0.586 - 0.758 GPa	Through thickness
Shear strength I	1.72 - 2.07 MPa	In plane
Shear strength II	5.52 - 6.89 MPa	Through thickness

2.2 Moisture properties

The moisture content of plywood is normally around 7-12% (dry basis) when the product leaves the mill, after that, the content can change during further process such as transportation or storage. The moisture content is defined by the initial mass tested (m_H) and the mass tested after drying the veneer (m_0), its formula is expressed below.

$$H = \frac{m_H - m_O}{m_O} * 100 \quad (1)$$

An increase of moisture content will result in a decrease of strength, shear modulus and elasticity modulus values. Besides, it is directly related to dimensional changes in and across the face grain direction, the thick of the ply, and the vapour permeability, which is greater when the moisture content increases. [4]

2.3 Durability properties

The biological properties of plywood are closed to its wood-raw material. It is susceptible to biological attacks, by fungi or other microorganism, if the moisture content is higher than 20% and oxygen is available [4]. For this reason, drying properly the veneers before gluing them is a very important part of the manufacturing process.

Finnish plywood is bonded with phenol formaldehyde glue which has excellent properties when is exposed to moisture and elevate temperature, despite of that, additional protection for the end grain and surfaces is important to avoid a possible degradation, which can cause delamination of the product. [3]

2.4 Applications

Plywood is a very mature product in the market of wood-based composite materials. The most common applications are construction, furniture, transportation, and packing. Since this product can form veneers into three-dimensional shapes, it is very attractive for the furniture industry, where it is used to make products such as chairs and tables. The proper ratios of stiffness and strength, in relation to weight, make plywood a suitable material for flooring in a wide range of applications such as trailers, railway wagons, vans and buses. This product is also used for a ship cargo holds and suitable for LNG tankers. In construction sector, it is used to make formworks, scaffoldings, and a huge amount of exterior and inside coatings such as roof elements, facades, or flooring. [3]

2.5 Future trends

The availability of wood logs to manufacture plywood is limited since this product has big competition with other sectors such as pulp and paper industry. However, new raw materials as beech wood are in development, and plywood could be made from non-wood species such as bamboo, changing, of course, their manufacturing process [3]. In this way, there is no reason to conclude that the production of plywood will be stopped in the future if this sector consumes efficiently the current raw materials and still developing technologies for the new ones.

More difficult task would be to change phenol formaldehyde glue to a renewable one. Bio-based resources such as lignin and vegetable oils have been studied to replace phenol formaldehyde, but their commercialization is not established yet. [3]

Lots of research, such as this thesis, are focused on increasing the functionality and the quality of plywood and its manufacturing process. A lot of improvements are being reached in this way, and it seems like it can be improved greater. New innovations can be expected, and following this future vision is done this project, where a vacuum contact dryer is studied in the fields of energy consumption and veneer properties as material.

3 Drying technologies

3.1 Veneer conditions and properties that affect drying

The most important factors that affect veneer drying are the properties of wood material and drying conditions.

Regarding the material, a relevant factor is veneer thickness. Thicker veneers need more time to get dried than thin ones. In addition, the thickness is not equal along veneers, encouraging uneven final moisture content. Another important factor is grain direction of veneer surface. Tangential grain dries several times slower than end grain (perpendicular to the grain direction and the growth rings), this fact is significant at the ends of veneers, where the drying is faster than in the main part. Consequently, it can provoke stresses and buckling in veneers. [6]

The flatness of dried veneer has a strong relation with mechanical pressure added during its drying. Thus, veneers dried between hot plates (contact drying) are the least buckled, and convective dryers with roller or wire-mesh conveyors reach flatter veneers than those dried in a kiln. [6]

In the point of view of moisture, the moisture content of Sapwood veneers is higher than the moisture content of those that are taken from a closer part to the centre, called as Heartwood (see Figure 2). Therefore, the drying times of the wetter parts (Sapwood) will be higher, a feature to keep in mind because it is possible to analyse logs from the same material but mixed trunk parts.

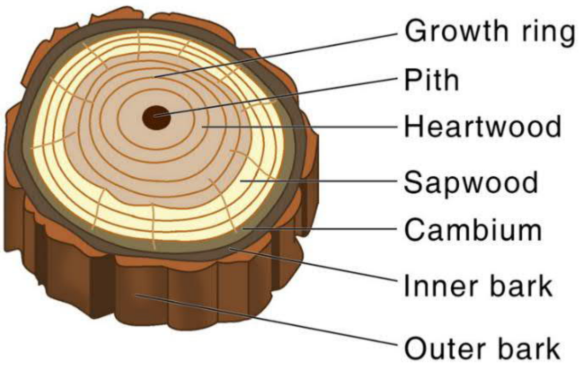


Figure 2. Parts of a Tree [7]

Furthermore, veneers after drying can be buckled depending on the dryer in which they are dried. Dryer with roller or wire mesh conveyor will produce straight veneer than veneers dried in a kiln and contact dryers with two flat-hot plates produce the least buckled. [6]

A strong relationship takes place between drying temperature and drying time because time can be highly reduced increasing the temperature. For example, the contact dryer of this project, which is explained in Section 3.3, under vacuum conditions and at 120°C needs 30 seconds to reach a moisture content of 35% for 1mm thickness veneers, but a moisture content of 4,5% is reached working at 200°C and the same time.

Contact dryer is the device with the fastest heat transfer because it is performed by conduction. In addition, it has better energy efficiency than the rest of dryers. Generally, working with the same temperature, a contact dryer needs less drying time than convective dryers, that use air circulation to transfer the heat.

3.2 Convective drying

Convective dryers are the most used in plywood industry. The present-day technology uses nozzles or jets to inject the hot air directly to the veneers, where removal of water is performed by evaporation. Progressive conveyors incorporated to these dryers, such as roller or wire-mesh, enables a continuous process. Roller dryers are used for thick veneers as 1.5 mm and wire-mesh dryers are used for thin veneers as 0.6 mm. [6]

A lot of methods and device have been made along the history of plywood, one type commonly used is the roller dryer with jets shown in Figure 3. The main parts are the blowers, that are used to circulate the steam into the dryer; the heaters; jet boxes; and the rollers, that also help to flatten veneers. [8]

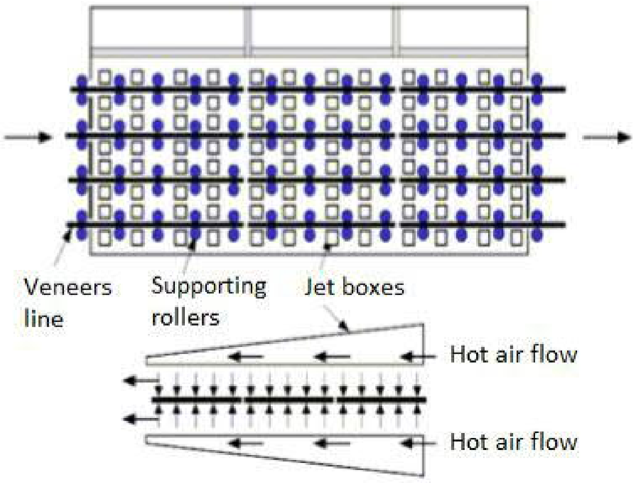


Figure 3. Schematic drawing of a convective dryer [8]

Some advantages of this technology, compared with contact drying technology, are the continuous drying process and larger industrial capacity. However, it has usually higher operational costs for electricity, since contact dryers have better energy efficiency.

3.3 Contact drying

Multi veneer hot-press dryer (see Figure 4) is one of the most common contact dryers, which use a hydraulic press and heated platens to dry the veneer by conduction because the platens are in contact with veneers during drying time. There are also a few industrial plants that use progressive platen dryers. [6]

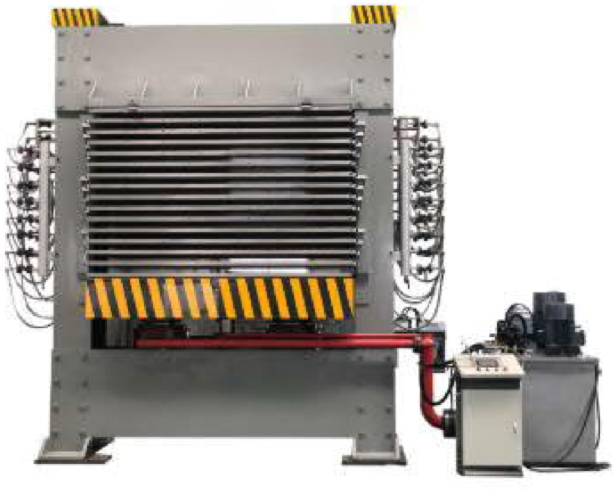


Figure 4. Multi veneer hot-press dryer from YUEQUN

Contact technology, with an effective heat transfer, works with shorter drying times and reaches lower values of final moisture content, although the large capacity necessary, for an industrial-plywood dryer, causes difficulties in its design. [9]

A simple schematic drawing of a new contact drying method, which is analysed in this project, is shown in Figure 5. This technology, in contrast to a common contact dryer, has a cold bottom plate (T_C), thus, only the top plate is electrically heated (T_H). Besides, it has a vacuum system which allows to work with lower boiling temperatures than those at atmospheric conditions (around 100°C), reducing drying times.

During veneer drying, the evaporated water goes to the cooling system where it turns to liquid again. There are two elements below the veneer that enable the evaporated water towards the cooling system: porous material and metal wire. Porous material stabilises the pressure between veneer and cooling system, and metal wire facilities the water removal.

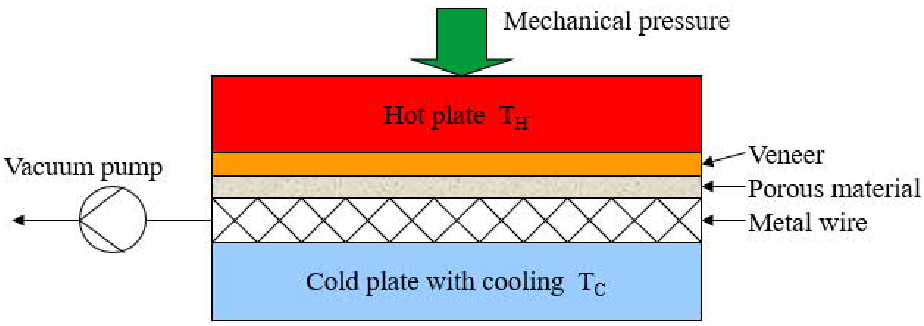


Figure 5. Schematic drawing of contact dryer patented at Aalto [9]

Some disadvantages related to contact drying could be a fouling of the plates due to volatile wood components, limited capacity as dryer and the slow process in as veneers are feeding into the dryer. However, contact drying is an interesting technology to get flatter veneers and working with better energy efficiency.

3.4 Drying-technologies comparison

The following table shows some data collected from both technologies explained. The difference between drying times is notable. Convective dryers need more time to dry veneers, although it can vary depending on the manufacturer. The times are based on one veneer drying to facilitate the comparison. Convective is a jet dryer as that showed in Figure 3 and Contact dryer is the device analysed in this project.

Table 3. Drying times from different convective and contact dryers

Dryer	*Temperature (°C)*	*P (bar)*	*H1 (%)*	*H2 (%)*	*Drying time (s)*	*Thickness (mm)*
Convective [10]	160	1	80	5	180	1.5
Contact [10]	160	1	73	5	90	1.5

In addition, Table 4 shows dryers available in the market with some characteristics parameters as drying capacity for convective dryers, layers number (number of veneers that can be dried simultaneously) for hot-press dryers and power. Roller and wire-mesh dryer type are related to convective technologies with a roller and wire-mesh conveyor, respectively.

Table 4. Collected data from convective and hot-press dryers available in the market

Model/Manufacturer	*Dryer Type*	*Drying capacity (m^3/h)* *Layers Number (LN)*	*Power (kW)*
BG1333/BSY [11]	Roller	4.8-5.5 m^3/h	168.5
BG183A/BSY [11]	Mesh-wire	5-5.8 m^3/h	190
HDR2-8/HANVY [12]	Roller	2.1 m^3/h	77.2
HDN3-10/HANVY [13]	Mesh-wire	4.5 m^3/h	139.5
YQHP4X8/YUEQUN [13]	Hot-press	15 LN	26
HDG-Z/WUXI HAOXIANG [14]	Hot-press	15 LN	15
GLVPD15/GEE LONG [15]	Hot-press	15 LN	15

In many cases, these convective dryers can be made with roller conveyor for thick veneers, wire-mesh conveyor for thin veneers or mixed conveyors depending on the client requirements. The large capacity of convective dryers and their continuous process make them as the best current technology for plywood industry.

4 Laboratory setup

4.1 Contact Dryer

The dryer used is a contact dryer patented at Aalto University. This device is also known as press dryer since it has a hydraulic piston for pressing both plates. The technology of this dryer is explained in Section 4.3.

A characteristic element is the vacuum pump, which allows to work under atmospheric pressure. A drying box with a sealing strip is essential to work under these conditions efficiently. The hydraulic press also helps a proper sealing as well as pressing the veneer to the hot plate, reducing drying times.

Figure 6 shows a picture of the laboratory contact dryer, where the main elements are listed in relation to Table 5, minus Pressure regulator valve (Element 9) which is shown in Figure 7.

Table 5. Main elements of the laboratory contact dryer

Number	*Element*
1	Cooling water feed
2	Pressure release valve
3	Control Unit of the hot plate
4	Electrically heated hot plate
5	Control Unit of Hydraulic press
6	Vacuum pump
7	Cooling system and drying box
8	Hydraulic press
9	Pressure regulator valve

Figure 6. Laboratory contact dryer

Figure 7. Pressure regulator valve

The following figures (from Figure 8 to Figure 10) show detailed pictures of some elements, where important components, such as valves or switches, are indicated.

Figure 8. Vacuum pump of the laboratory contact dryer

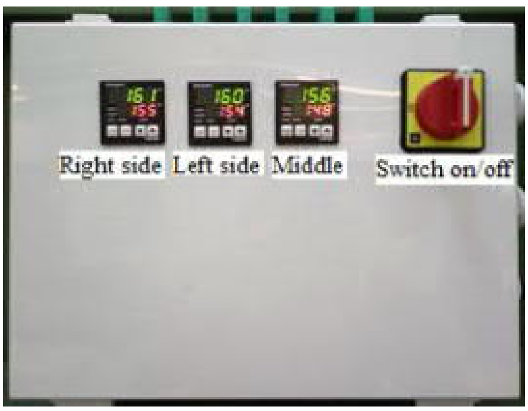


Figure 9. Control Unit of the hot plate

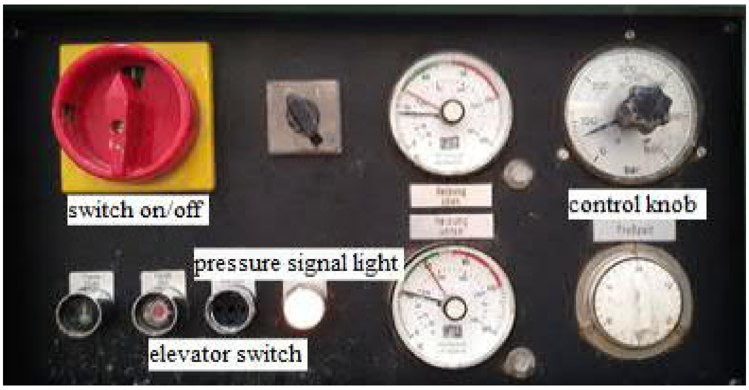


Figure 10. Control Unit of Hydraulic Press

4.2 Computer interface

The operations of the dryer are controlled by three programs called Vacuum Control, Automatic Press and Data Logger, that are shown in Figure 11, Figure 12, and Figure 13, respectively.

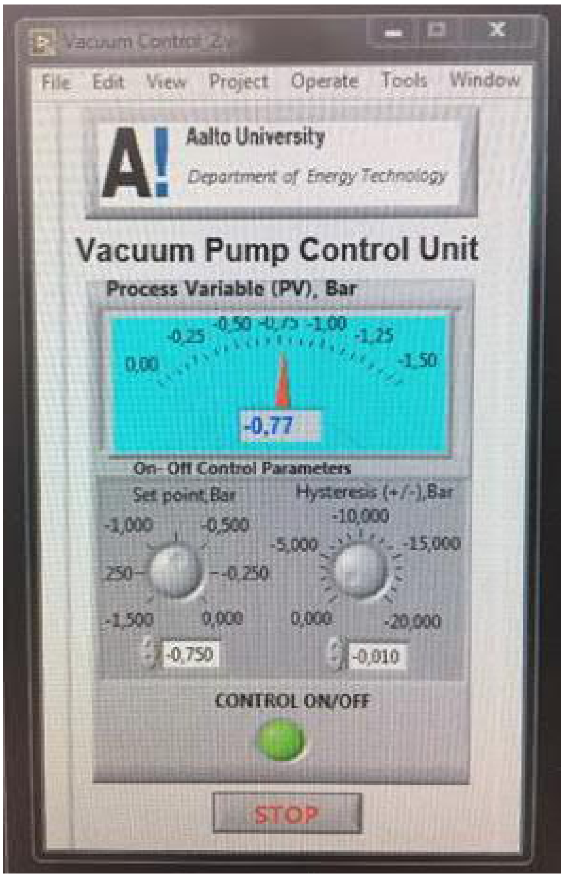


Figure 11. Vacuum Control program

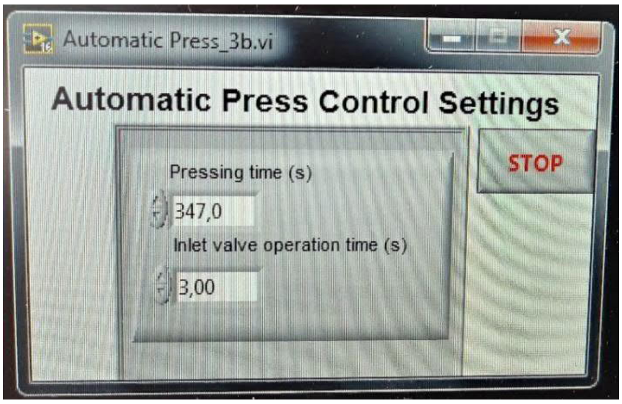


Figure 12. Automatic Press Control program

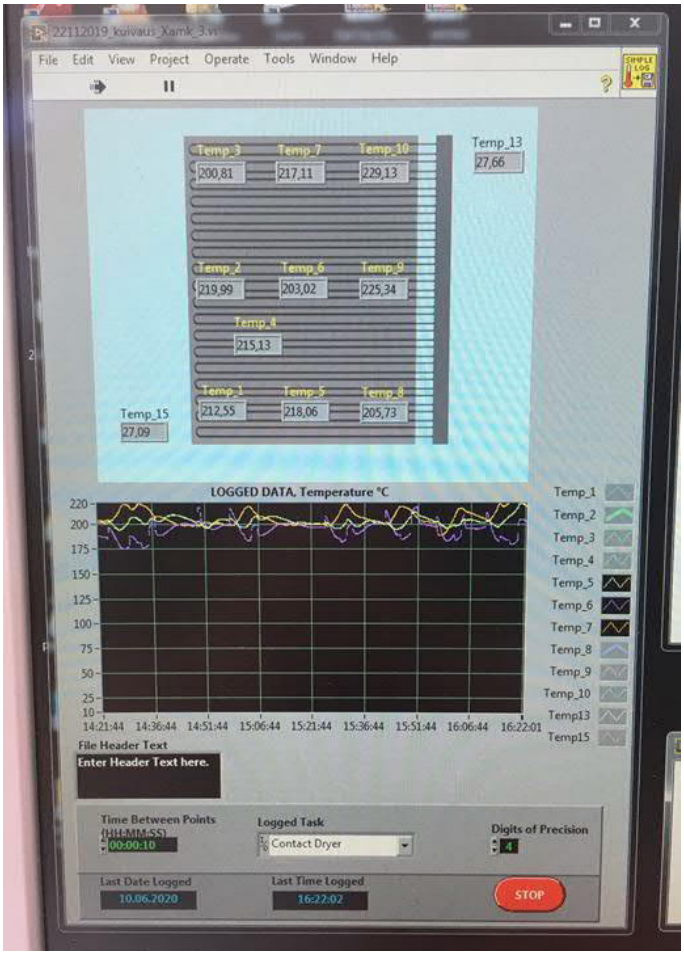


Figure 13. Data Logger program

The pressure inside the drying box is regulated by Vacuum Control, which works with gauge pressure. As it is shown in Figure 12, a value of -0.75 bar must be set in the program if 0.25 bar pressure is required. To achieve the desired pressure, the pump only runs at the beginning of the drying time, improving the efficiency of the system significantly. Then, the pressure regulator valve opens when the pressure exceeds the fixed pressure plus hysteresis value, and it closes when the pressure decreases bellow of the fixed value minus hysteresis value.

When a veneer is inside the drying box, the elevator switch of Control Unit of Hydraulic press is used to elevate the drying-box platform until sealing the drying box with the hot plate and reaching the set mechanical pressure between them. At this moment, the pressure signal light is lit, and Automatic Press starts to count down from the set value called as Pressing time. When this value is reached, Pressure release valve opens for a specified period called Inlet valve operation time, after that the press opens automatically. It is important to keep in mind that the drying time is equal to Pressing time plus Inlet valve operation time. Therefore, Pressing time set in the program should be the drying time minus Inlet valve operation time. For example, Pressing time should be 27 seconds and 3 seconds of Inlet valve operation time if 30 seconds of drying time is desired.

Data Logger program is used to show and record temperature values of ten points of the heat plate, and cooling water inlet and outlet temperatures. This program is useful to compare the values shown on the program with the values fixed in Control Unit of the hot plate and controlling if the temperature is similar around the hot plate, that is an important feature to get an even drying.

4.3 Measurement devices

The basic data to be recorded is veneer identification code, drying time, veneer mass before and after drying, drying pressure and hydraulic pressure. A rudimentary scale is used for veneer mass before and after drying (see Figure 14). This device has 0.1 grams resolution, which is enough to compare veneer masses.

Figure 14. PRECISA 6000D scale

5 Measurements

5.1 Start steps for a measurement session

There are some mandatory steps to ensure a correct dryer work.

1. Checking the vacuum pump oil, which should be in the middle of its sight glass, and quality. The appropriate state is a clear and transparent oil.
2. To turn on the vacuum pump and running it for 30 minutes with the intake valve of the pump (see Figure 7) closed.

3. To switch on the hot plate and, after waiting a short time, to set the plate temperatures represent on the screens that show the three divided parts of the hot plate: middle, right, left (see Figure 9).
4. To switch on the Control Unit of Hydraulic press, and to set veneer surface pressure using control knob and a pressure-conversion table.
5. To turn on the cooling water flow and to adjust its water flows in case that it would be necessary.
6. To switch on the computer.
7. To turn on valve controller, power supply unit, sensor interface.
8. Opening the control programs: Vacuum Control, Automatic Press and Data Logger.

5.2 Measurement procedure

When Vacuum pump is running 30 minutes with its intake vale closed, it can open, and the dryer is ready for measurements if manual air inlet valve and condensate water removal valve are already closed. It is also important to check every measurement if the sealing strip is in its groove since it comes out easily, a fact that could break the strip or reach air leak into the drying box.

Veneer measurement can start when Data Logger is running and the operational conditions such as drying pressure and time are set in their programs, as it is explained in Section 5.2. The control programs keep running during all the measuring session and they are stopped only for changing the set values.

Veneer-measurement procedure has several sequential steps: to put a veneer on the wire (porous material); to close Hydraulic press, using the elevator switch of its control unit until the pressure signal light is lit; and taking the veneer out when the drying-box platform returns to its initial position. This procedure is divided in veneer logs to compare drying times and moisture contents of veneers from the same material and similar properties, such as density or initial moisture content.

The reference values in the measurements were 1.5 mm thickness, 160°C for the hot plate and 250 mm bar of vacuum pressure. In this way, three different veneer-thickness were analysed keeping the same dryer conditions (160°C and 250 mm bar): 0.6, 1.5 and 3 mm. The thin veneers belong to Birch wood and the thicker ones (3 mm) to Spruce. In addition, some data of 1 mm, which was collected from previous measurements sessions of this thesis, was also analysed. In this case, the hot plate worked at 120, 160 and 200°C for 250 mbar and 160°C for atmospheric pressure in the drying box. The following table shows a summary of the initial values set in the dryer.

Table 6. Summary of initial values fixed in the dryer

Thickness (mm)	*Temperature (°C)*	*Pressure (mbar)*	*Wood material*
0.6	160	250	Birch
1	120	250	Birch
	160	250	Birch
	160	1000	Birch
	200	250	Birch
1.5	160	250	Birch
3	160	250	Spruce

When a lab session is finished, the curve of moisture content in relation to drying time can be done with the recorded values. If the obtained curve is suitable, one work parameter will be changed, for the next session, in relation to the work conditions fixed previously as reference.

5.3 Closing steps for a measurement session

As there are mandatory steps for the beginning of a measurement session, it is necessary to follow some steps for the end.

1. Keeping the pump running for 30 minutes with its intake vale closed.
2. To switch of the control units of the hot plate and Hydraulic press.
3. To turn off the valve of cooling water flow.
4. Opening the condensate water removal valve to drain excess water from the drying box.
5. Checking that there is no water behind the manual air inlet valve.
6. Cleaning the hardware of wood splinters or similar if necessary, leaving the dryer in suitable conditions.
7. Closing the control programs after taking a copy of measurement data in case that it would be necessary.
8. To switch off the computer.
9. To turn off valve controller, power supply unit and sensor interface.

6 Results

The data is recorded in an Excel table during measurement session. Veneers are identified by one letter and one number. The letter informs log of origin and the number is put on veneers in the order that they are dried. Table 7 and Table 8 show a table-example of the thinnest veneers (0.6 mm).

Veneers are dried at least two times, since it is necessary to get initial-moist mass (m_0), mass after the first drying (m_1) and dried mass (m_2), that are required values to calculate initial moisture content (H_1) and moisture content after drying (H_2).

$$H_1 = \frac{m_0 - m_2}{m_2} * 100 \ (2) \quad H_2 = \frac{m_1 - m_2}{m_2} * 100 \ (3)$$

The parameter called as "dm" represents the difference between initial and after-drying masses, which is useful to check how is the dryer working during the session; t_1 is the first drying time; t_2 is the drying in which dried veneer is reached; the showed thickness indicates the nominal one; T(°C) is the set temperature of the hot plate, which is not constant during the session but it varies close to the set value every time; and P(mbar) is the pressure inside the drying box performed by Vacuum pump.

Table 7. Example of Excel table recorded during a measurement session (I)

Veneer	m_o	m_1	m_2	$dm(m_o - m_1)$	H_1	H_2
i1	404	238,3	202,3	*165,7*	99,70%	17,80%
i2	418,5	293	196,5	*125,5*	112,98%	49,11%
i3	426,5	309,3	206,7	*117,2*	106,34%	49,64%
i4	427,5	299,8	218,3	*127,7*	95,83%	37,33%
i5	417,7	295,7	213,5	*122*	95,64%	38,50%
i6	407,5	211,3	198,7	*196,2*	105,08%	6,34%
i7	404,2	210,1	198,1	*194,1*	104,04%	6,06%
i8	413,6	224,1	213,6	*189,5*	93,63%	4,92%
i9	411,1	218,3	207,1	*192,8*	98,50%	5,41%
i10	409,6	221,3	211	*188,3*	94,12%	4,88%
i11	414,4	229,5	216,1	*184,9*	91,76%	6,20%
i12	390,8	246,6	211,3	*144,2*	84,95%	16,71%
i13	392	241,7	203,6	*150,3*	92,53%	18,71%
i14	406,1	250	212,1	*156,1*	91,47%	17,87%
i15	405,6	216	214,3	*189,6*	89,27%	0,79%
i16	398,2	213,7	209,7	*184,5*	89,89%	1,91%
i17	398,8	214	209,8	*184,8*	90,09%	2,00%

Table 8. Example of Excel table recorded during a measurement session (II)

Veneer	t_1	t_2	*thickness (mm)*	*T(°C)*	*P (mbar)*
i1	20	30	0,6	160	250
i2	10	70	0,6	160	250
i3	10	70	0,6	160	250
i4	10	70	0,6	160	250
i5	10	70	0,6	160	250
i6	30	60	0,6	160	250
i7	30	60	0,6	160	250
i8	30	60	0,6	160	250
i9	30	60	0,6	160	250
i10	30	60	0,6	160	250
i11	30	60	0,6	160	250
i12	20	70	0,6	160	250
i13	20	70	0,6	160	250
i14	20	70	0,6	160	250
i15	40	40	0,6	160	250
i16	40	40	0,6	160	250
i17	40	40	0,6	160	250

6.1 Drying curves

The curves are assimilated to a decreasing-polynomial equation as drying time is longer. The accuracy of the curves can be realised by the coefficient of determination (R^2), which should be closed to 1. The abscissa points (drying times) increase until reaching dried veneers. The final points depend on the characteristics of the veneers. Thus, large drying times belong to veneers with high initial moisture content or/and thick veneers.

In practice, the drying times start with 10 seconds, although a previous point, which is calculated with the average of initial moisture contents, is used to obtain a full drying curve. Moreover, every drying time has been repeated at least two time to take in account possible variations in initial veneer conditions, such as moisture content or branch marks.

The title of the curve indicates the main work conditions: veneer thickness (mm), hot-plate temperature (°C) and drying pressure (mbar). The following pictures (from Figure 15 to Figure 26) show the drying curves obtained from the measurement sessions, where orange and blue points represent initial and final moisture contents (after drying), respectively. The curves are presented from those based on thinnest veneers to the thickest ones.

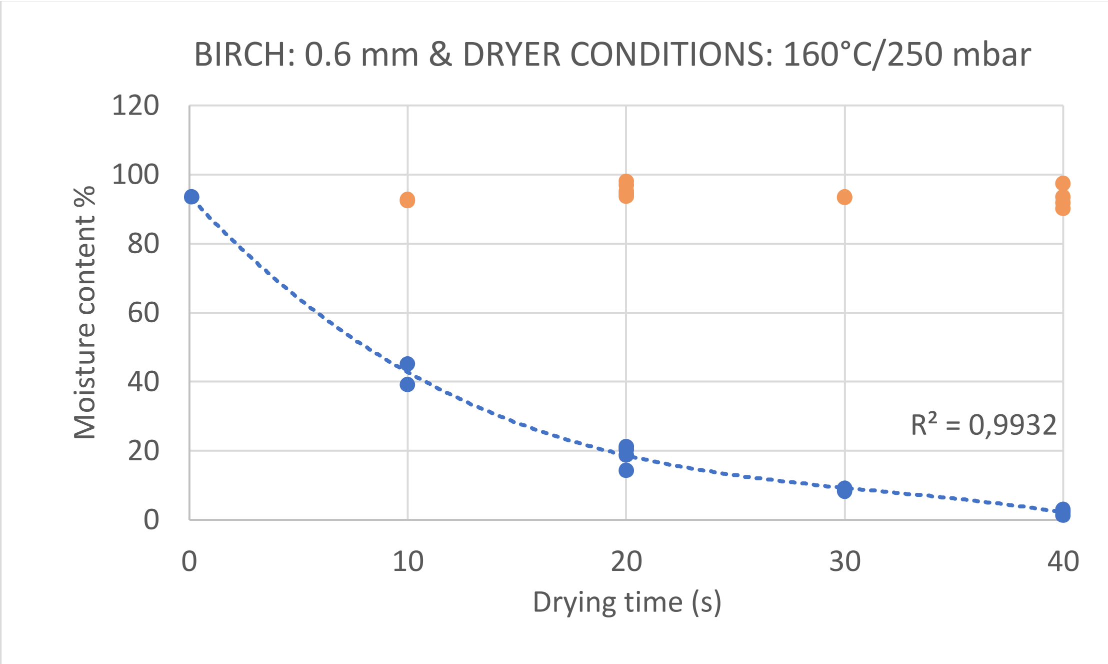


Figure 15. Drying curve for veneers of 0.6 mm thickness and dryer conditions of 160°C and 250 mbar (I)

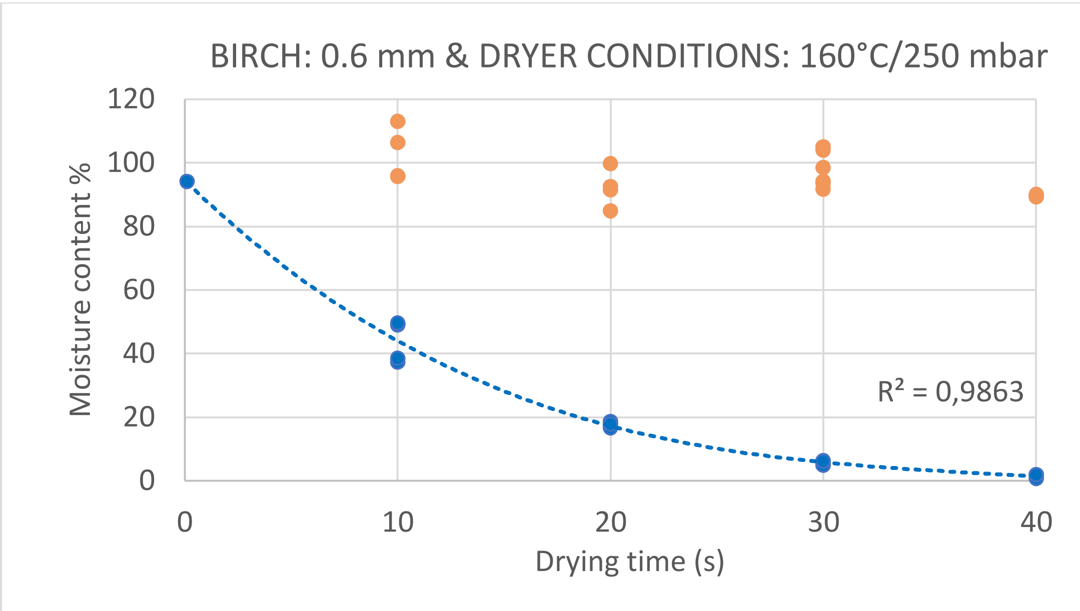


Figure 16. Drying curve for veneers of 0.6 mm thickness and dryer conditions of 160°C and 250 mbar (II)

As it is shown in Figure 15 and Figure 16 related to two different measurement sessions, a dried veneer of 0.6 mm is reached for 40 seconds. Besides, there is an initial heat shock (first 10 seconds) where veneers are dried more than half of initial moisture content. This fact is a result of the first contact between veneer and hot plate, when gases inside veneer mechanically expand and push part of "free water" out of veneer. After that, the drying goes slower until reaching a fully drier veneer at 40 seconds in both curves.

The following curves belong to 1mm thickness. In the surveyed data, there are three different temperatures and two working pressures. Thus, comparative curves of temperatures and pressures are also presented.

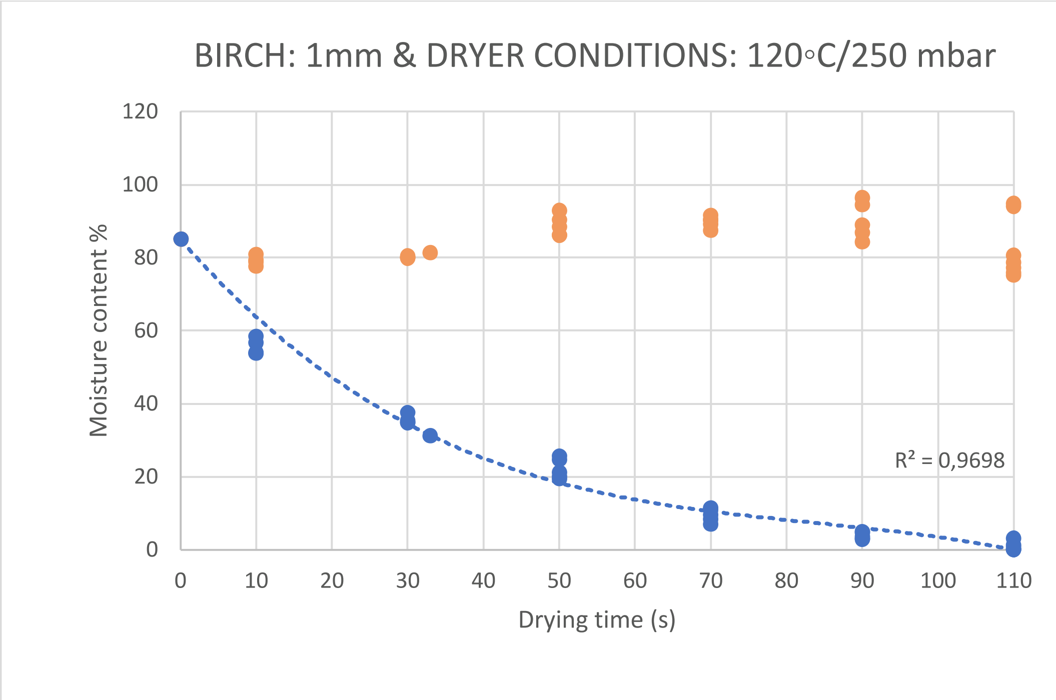


Figure 17. Drying curve for veneers of 1 mm thickness and dryer conditions of 120°C and 250 mbar

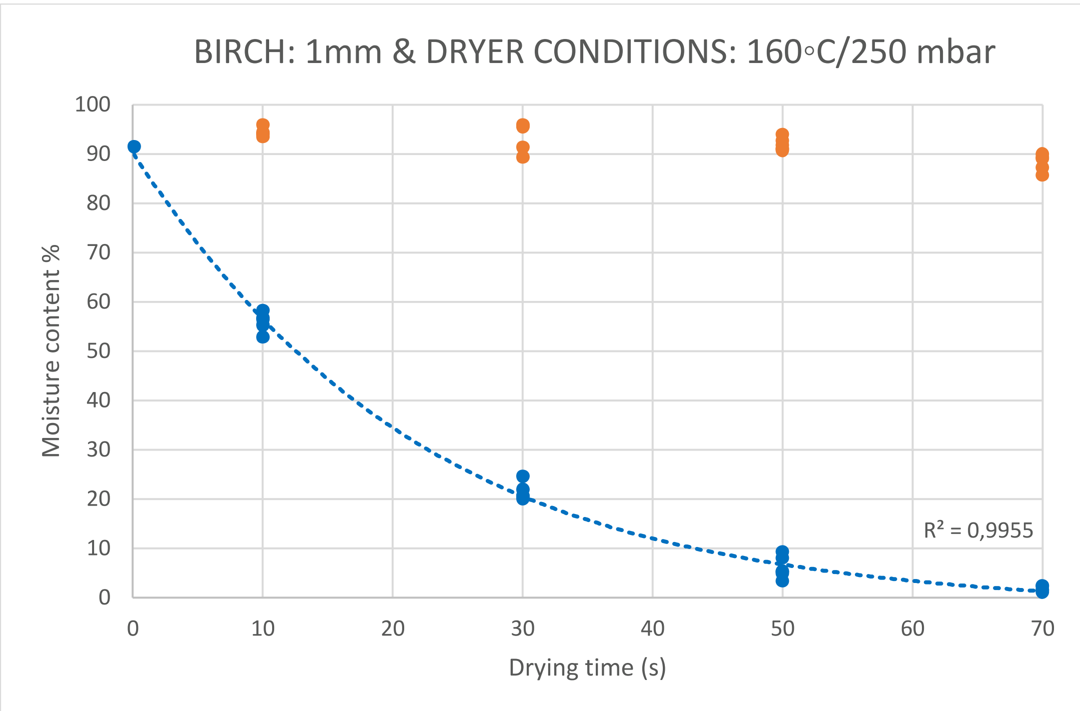


Figure 18. Drying curve for veneers of 1 mm thickness and dryer conditions of 160°C and 250 mbar

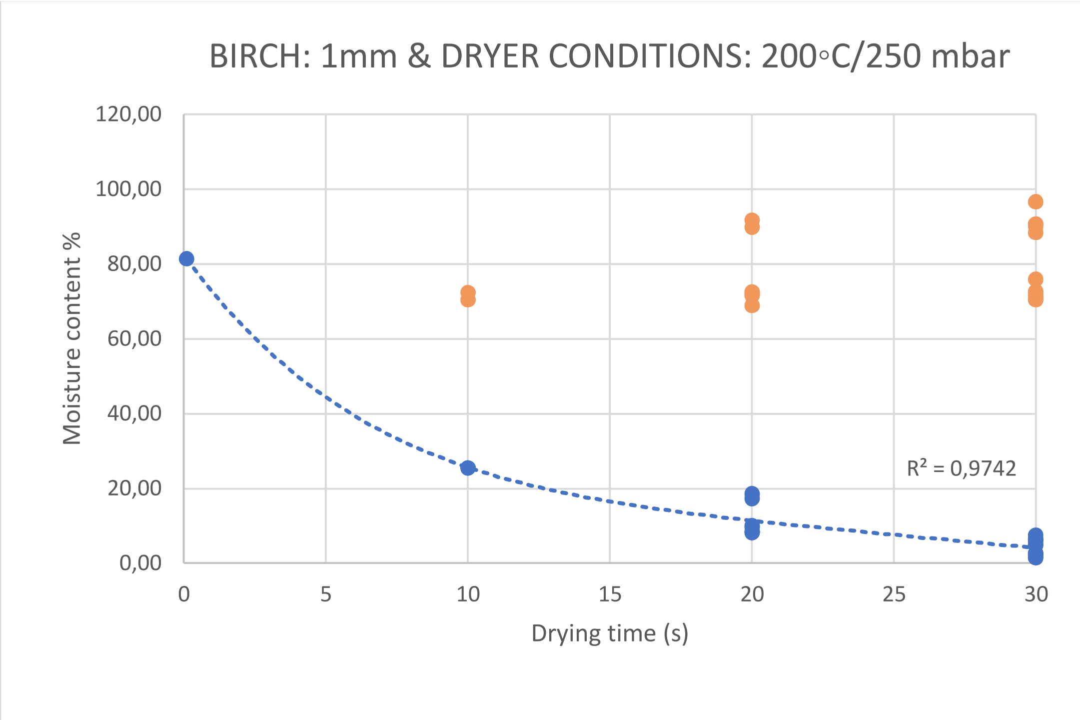


Figure 19. Drying curve for veneers of 1.5 mm thickness and dryer conditions of 160°C and 250 mbar (I)

Comparing these curves of 1 mm at different temperatures, it is easy to realise how the hot-plate temperature affect the required drying time. Working at 120°C, a dried veneer is reached for 110 seconds. This value decreases 40 seconds for 160°C, and the same for 200°C, being almost dried at 30 seconds. Therefore, it seems there is a similar relationship between temperatures and drying times, in which the drying decreases 40 seconds when the heated plate increases its temperature 40°C. The initial shock also increases with the temperature. It is two times bigger working at 160°C than 120°C. For 200°C, it also increases compared to 160°C, although it is not significant. These comments are reflected on the following graphic where all the curves of 1 mm are presented together. The colours represent each working temperature, the shaded points represent the moisture content after drying (H_2), and the circles from the same colour represent its initial moisture content (H_1).

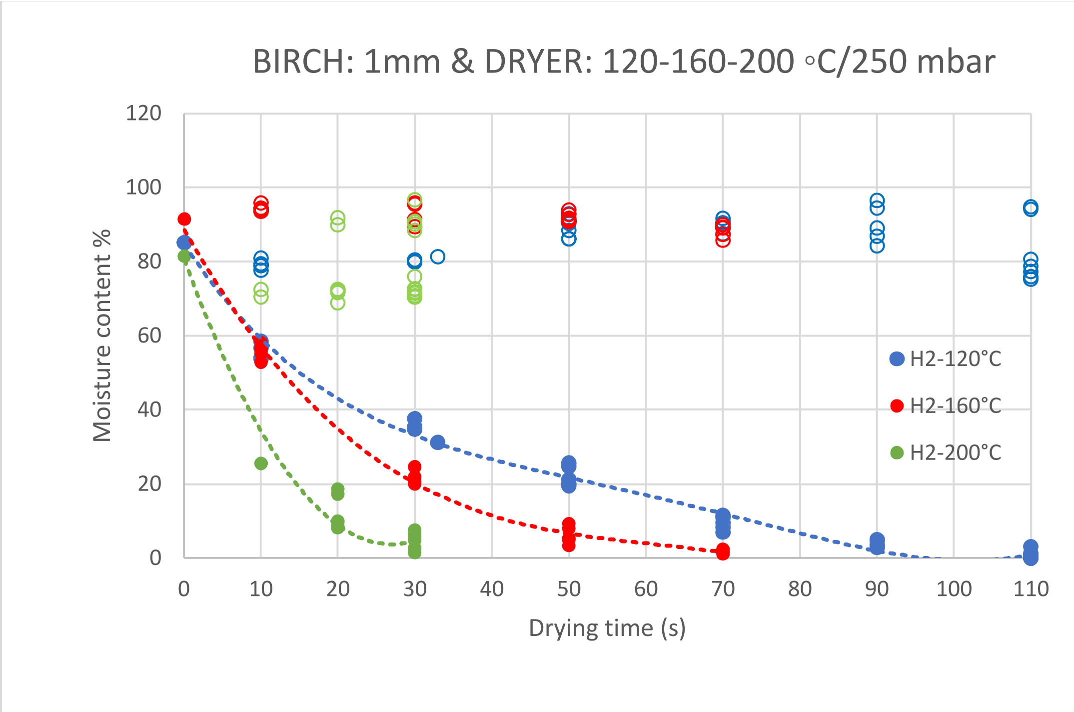


Figure 20. Comparative drying graphic of temperatures for veneers of 1 mm thickness

Figure 21 shows the drying curve when the vacuum pump is not working. Hence, the pressure inside the drying box is the atmospheric. It seems the curve when the vacuum pump is working, but some differences can be found comparing both in detail. This comparison allows us to understand the vacuum effect in drying process.

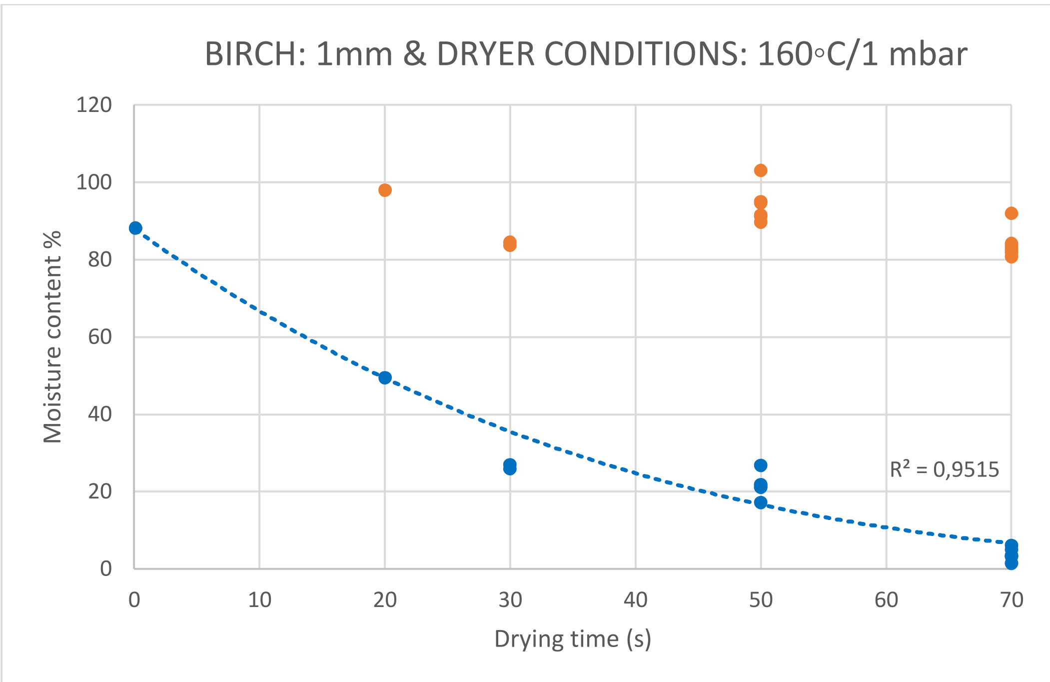


Figure 21. Drying curve for veneers of 1 mm thickness and dryer conditions of 160°C and 1 bar

Figure 21 is compared with Figure 18 to get the differences between working at atmospheric pressure and vacuum pressure (Figure 22). A proper point to see the vacuum effect is 50 seconds where a dried veneer is almost reached working at 250 mbar (average point 5,5%) and, for atmospheric pressure, the average point of moisture content is quite higher, being 21,63%.

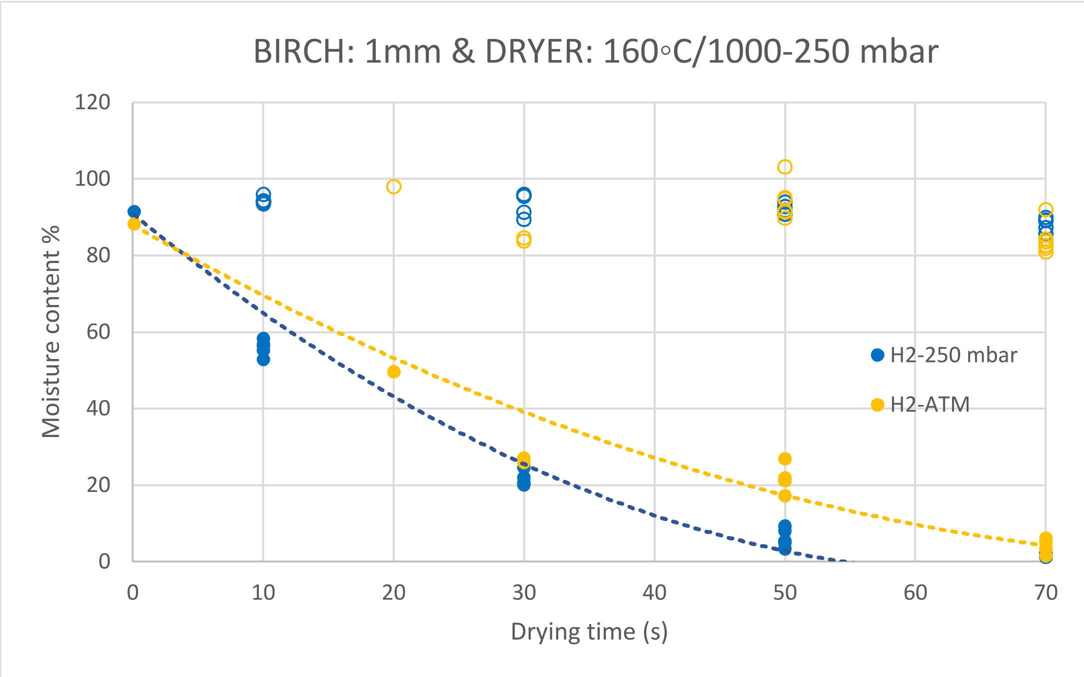


Figure 22. Comparative drying graphic of pressures for veneers of 1 mm thickness

The drying curves of 1,5 mm thickness are divided into two different groups. One group belong to veneers of initial moisture content between 65% and 80% (Figure 23), and another veneers group from 94% to 113% (Figure 24). Thus, it is easier to compare veneers of similar moisture content. Since the initial moisture content have an important impact on final drying time, the first curve reaches dried veneers before than the second one.

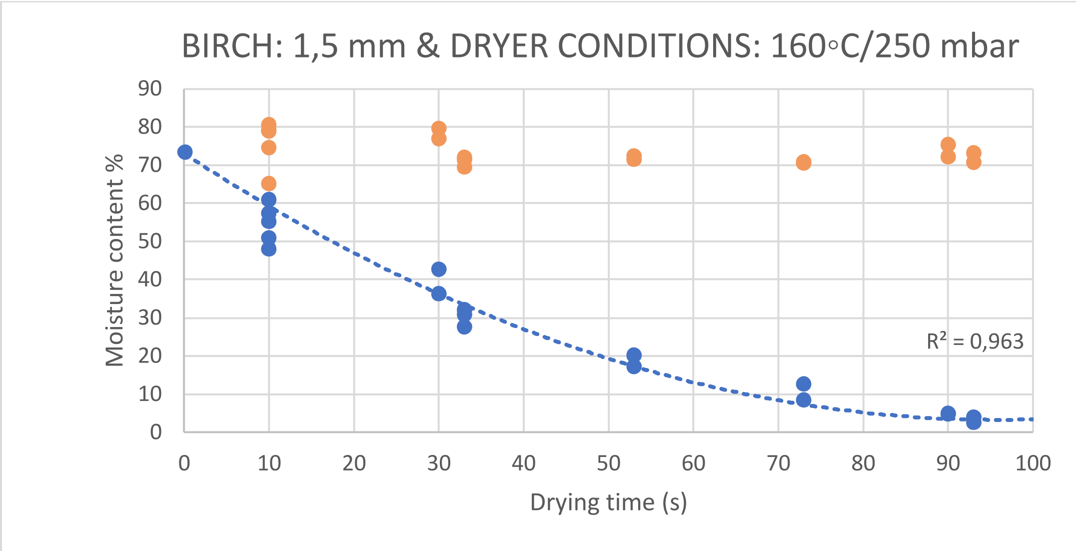


Figure 23. Drying curve for veneers of 1.5 mm thickness and dryer conditions of 160°C and 250 mbar (I)

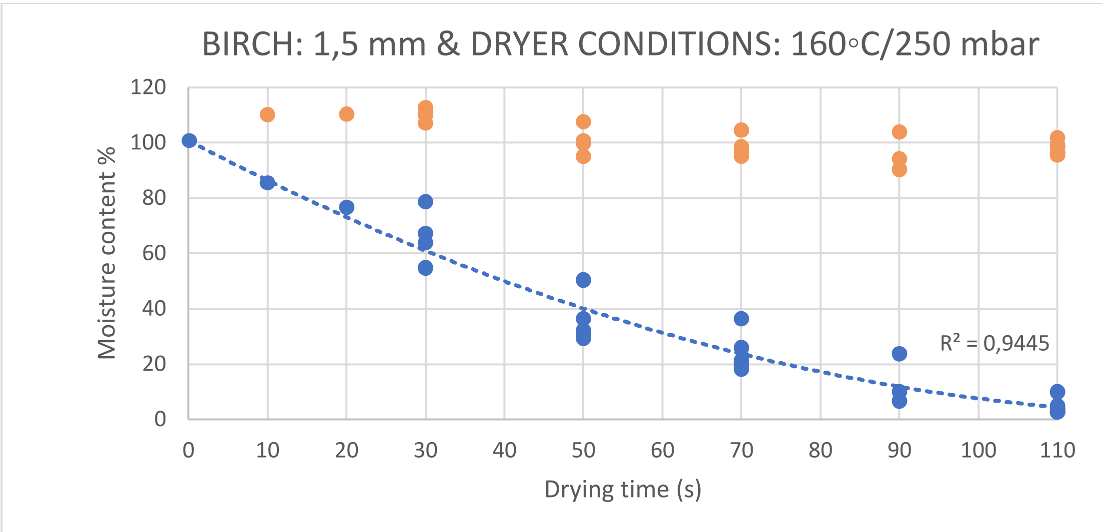


Figure 24. Drying curve for veneers of 1.5 mm thickness and dryer conditions of 160°C and 250 mbar (II)

For 1,5 mm thickness, the curves are more linear than the previous cases. In Figure 23, the initial shock is around 20% and a similar amount of moisture is removed for 30 seconds. Then, the slope of the curve goes slower until reaching a dried veneer for 90 seconds. The second curve has a lineal trend for the first 70 seconds. After that, the final 20% of moisture content is removed during the next 40 seconds.

The following curves are based on veneers of 3 mm thickness, where different parts of the trunk, such as sapwood or heartwood, were analysed. This fact caused a huge variation of initial moisture contents. For this reason, veneers have been divided into three groups of initial moisture content: high, medium, and low. The first curve has an initial-moisture-content average of 92,58% (Figure 25), the average of the second one is 159,38% (Figure

26), and 35% for the third curve (Figure 27). Therefore, the required drying times are different in each curve.

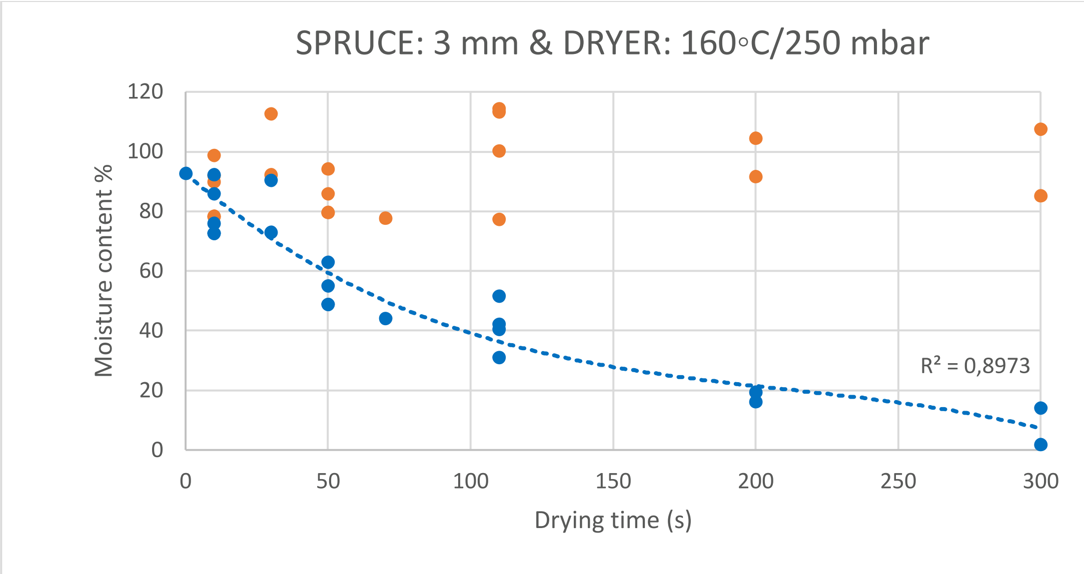


Figure 25. Drying curve for veneers of 3 mm thickness and dryer conditions of 160°C and 250 mbar (I)

In Figure 25, the drying goes faster for the first 110 seconds, where half of the initial moisture content is removed, approximately. The rest is removed for the following 190 seconds, getting a dried veneer at 300 seconds.

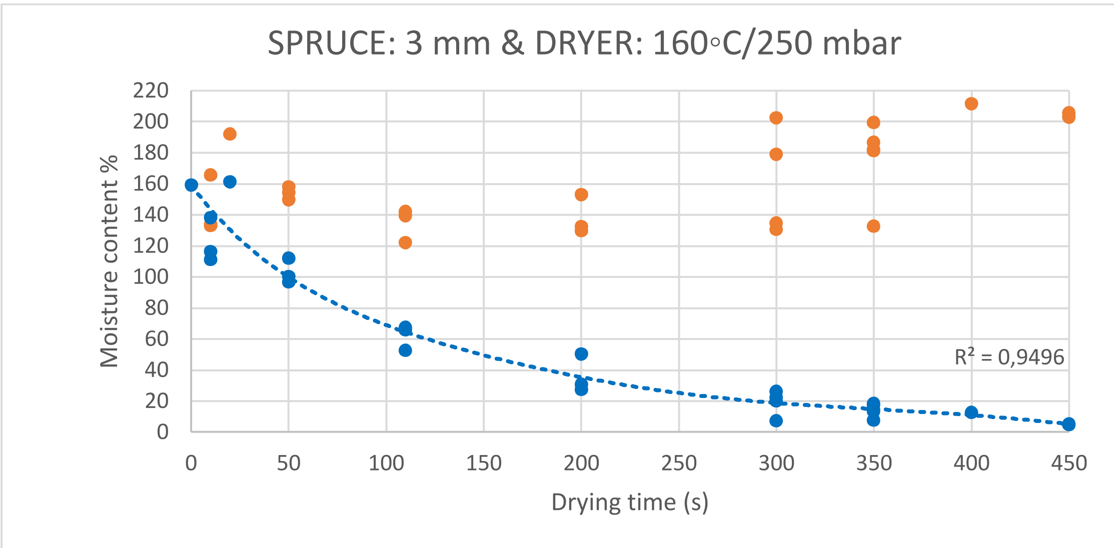


Figure 26. Drying curve for veneers of 3 mm thickness and dryer conditions of 160°C and 250 mbar (II)

Figure 26 has the longest drying times compared with all the surveyed data, because it has veneers of very high initial moisture content (200%) plus they are the thickest ones. A dried veneer is achieved at 450 seconds in the case of the moistest veneers. For those with lower moisture as 140%, 400 seconds is enough.

The following curve shows the lowest initial-moisture-content veneers. For that, shorter drying times are needed. In this case, more than half amount of moisture is removed at 90 seconds, and a long time is required to dry 10% more.

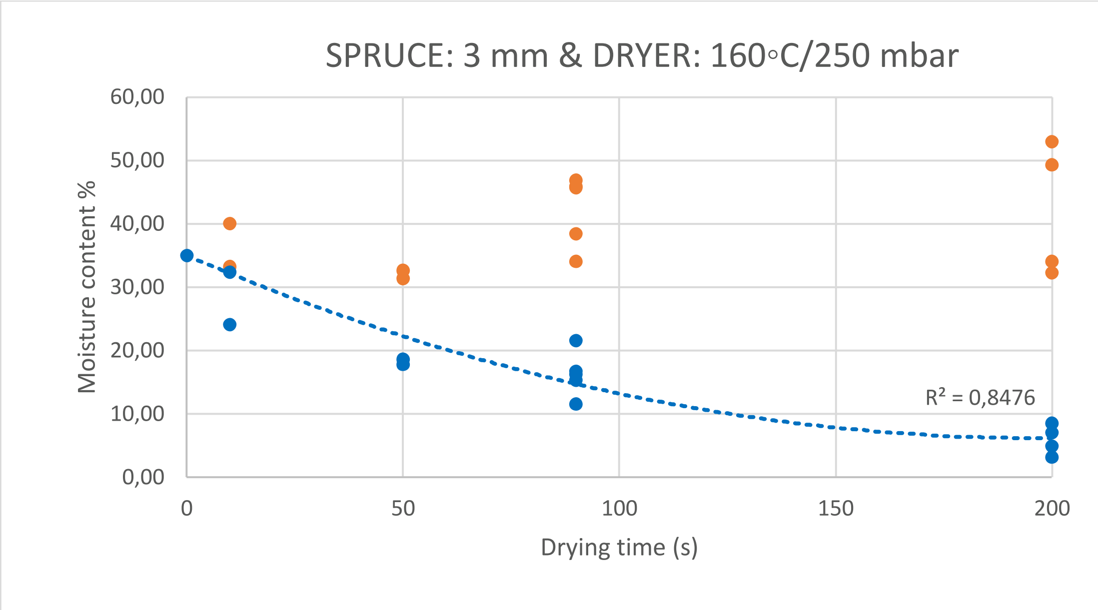


Figure 27. Drying curve for veneers of 3 mm thickness and dryer conditions of 160°C and 250 mbar (III)

The previous curve shows the slow process of drying veneers of 3 mm thickness, where 200 seconds are required for drying a veneer of only 40% in moisture content. Besides, it seems that the thickest veneers do not allow an initial drying shock, as it happens for thinner veneers.

In addition, the presented curves of 160˚C-250 mbar work conditions were analysed jointly in a comparative graphic to appreciate easier the differences between each other, from a point of view of thickness effect. This graphic is shown in Figure 28, where four different colours represent the four thickness.

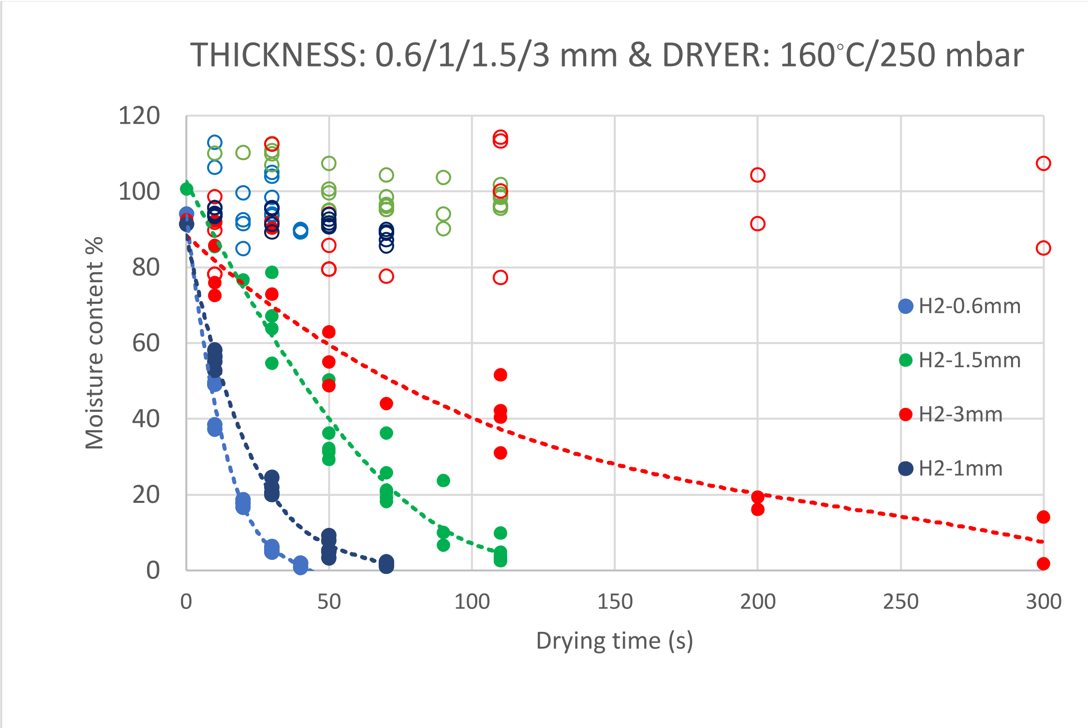


Figure 28. Comparative drying curve of thickness effect working at 160°C and 250mbar

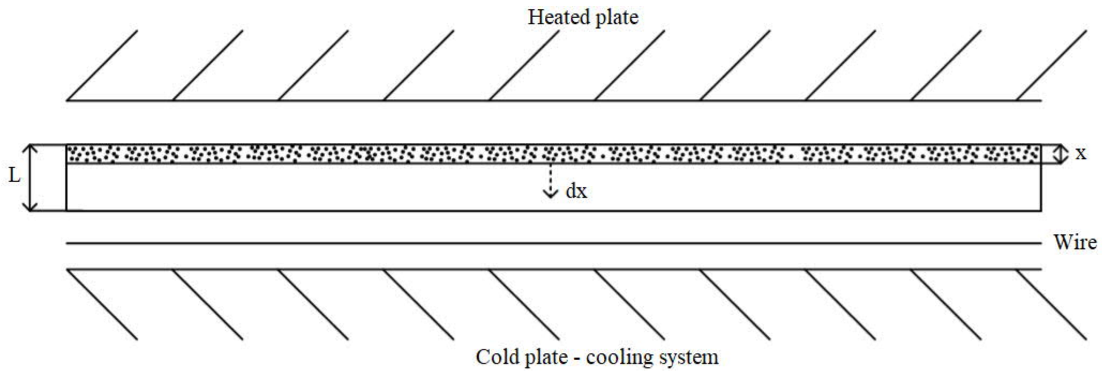
As it is shown in Figure 28, dried veneers are reached at 40 seconds for 0,6 mm, increasing 30 seconds for 1 mm veneers, and only 40 seconds more for 1,5 mm (110 seconds). In contrast, 300 seconds are required at least to dry veneers of 3 mm. Therefore, the final drying time is quite proportional with thickness until 1,5 mm, but it escalates notably for 3 mm.

The thickness has a strong relation with the curve slope, although this is not similar for all the thickness. It seems that the differences in drying times are higher between thicker veneers. For example, the differences between 0,6 mm and 1,5 mm are lower than 1,5 mm and 3 mm, despite the thickness is more than double in the first case.

The curve of 1,5 mm can be a suitable reference since it has the most linear behaviour compared with the rest of the thickness. Besides, it has a close relation between moisture content and drying time, being the slope around one. Thus, if we work with less thickness than 1,5 mm, we know already that we will get less drying time in seconds than initial moisture content in percentage, and the opposite way for higher thickness. An important feature to set the times in the dryer and monitoring this contact-drying process.

7 Modelling of drying time

A drying-time model is proposed to describe the veneer drying using the laboratory contact dryer, which has only the up-plate electrically heated. The heat transfer takes place from the surface in contact with the hot plate to the other veneer face, and the same way for the evaporated water, that will be collected into the cooling system.



The model considers that there is a dry thickness (x), or depth of the evaporated zone, expanding during drying. Following this feature, a simplified heat balance is assumed in Formula 4 with the parameters: weight of liquid water per unit volume (C_{H2O}), latent heat of water evaporation (ʎ), contact area between the hot plate and veneer surface (A) and dry thickness. [7]

$$\frac{dQ}{dt} = C_{H2O} * ʎ * A * \frac{dx}{dt} \quad (4)$$

A second equation (Formula 5), which is required since the heat transfer is unknown, is obtained from the law of heat conduction, also known as Fourier's law.

$$\frac{dQ}{dt} = \frac{k * A}{x} * (T_s - T_b) \quad (5)$$

where k is thermal conductivity of dry wood; T_s is surface temperature, which is equal to the hot plate temperature; and T_b is boiling temperature of water.

Combining Formula (4) and (5) and arranging the parameters:

$$dt = \frac{x}{k * (T_S - T_b)} * C_{H2O} * ʎ * dx \quad (6)$$

and drying time equation (Formula 7) is obtained integrating Formula 6.

$$t = \frac{x^2 * C_{H2O} * ʎ}{2 * k * (T_S - T_b)} \quad (7)$$

C_{H2O} is defined as weight of liquid water per unit volume, where the volume (V) can be calculated as the weight of dry wood (w_{dw}) divided into wood density (ƒ).

$$V = \frac{w_{dw}}{ƒ} \quad (8)$$

$$C_{H2O} = \frac{w_{H2O}}{V} \quad (9)$$

Thus, C_{H2O} can be arranged as:

$$C_{H2O} = \frac{\rho * w_{H2O}}{w_{dw}} \quad (10)$$

Taking the equation of initial moisture content from Section 4.1 (Formula 2); knowing that w_{H2O} is the difference between initial mass (m_0) and dried-veneer mass (m_2), where w_{dw} is the same as m_2; and combining these parameters with Formula 10, C_{H2O} can be rearranged as it is shown in Formula 12.

$$H_1 = \frac{m_0 - m_2}{m_2} * 100 = \frac{w_{H2O}}{w_{dw}} * 100 \quad (11)$$

$$C_{H2O} = \frac{H_1}{100} * \rho \quad (12)$$

On the other hand, the dry thickness is defined as a value, from 0 to veneer thickness (L), that increases with the drying time. This value will be equal to the veneer thickness when the veneer is totally dried, in other words, when the final moisture content (H_2) is 0%. Hence, the dry thickness can be defined as follows:

$$x = L * \left(\frac{H_1 - H_2}{H_1}\right) \quad (13)$$

Finally, combining the presented formulas ((7), (10), (12) and (13)), the final equation of drying time is reached, as it is shown in Formula 14.

$$t = \frac{H_1 * \rho * \lambda * L^2 * \left(1 - \frac{H_2}{H_1}\right)^2}{100 * 2 * k * (T_s - T_b)} \quad (14)$$

where wood density can be easily calculated using Formula 15, with the values of dried-veneer mass (m_2) and veneer dimensions, and the thermal conductivity is calculated from a suggested formula (Formula 16) by Kollmann and Cote [16], and the obtained values were contrasted with other technical reports [16].

$$\rho = \frac{m_2}{l * w * L} \quad (15)$$

$$k = 0.000195 * \rho + 0.025 \quad (16)$$

The following example shows the calculation process done to model drying time. The presented veneer belongs to m-log which comes from a Birch trunk and 1.5 mm thickness.

Table 9. Example of Excel table used for drying-time model (I)

Veneer	m_o(g)	m_1(g)	m_2(g)	H_1	H_2
m1	1089,300	691,200	637,500	70,87	8,424

$$H_1 = \frac{m_0 - m_2}{m_2} * 100 = \frac{1089.3 - 637.5}{637.5} = 70.87\%$$

$$H_2 = \frac{m_1 - m_2}{m_2} * 100 = \frac{691.2 - 637.5}{637.5} * 100 = 8.424\%$$

Table 10. Example of Excel table used for drying-time model (II)

t_{exp}	thickness	ƒ (kg/m3)	K (W/m*K)	T_s(˚C)	P (mbar)
73	1,50	708,333333	0,163125	160	250

$$ƒ = \frac{m_2}{L*w*l} = \frac{637.5}{0.6*1*1.5} = 708.33 \text{ kg/m3} \ (15)$$

$$k = 0.000195 * ƒ + 0.025 = 0.163125 \text{ W/m} * \text{K} \ (16)$$

Table 11. Example of Excel table used for drying-time model (III)

T_b (˚C)	ʎ (kJ/kg)	T_s(K)	T_b(K)	P (Pa)	t_m(s)	% error
65,1	2345,1	433,15	338,25	25000	66,424	9,90

$$t_m = \frac{H_1 * ƒ * ʎ * L^2 * (1 - \frac{H_2}{H_1})^2}{100*2*K*(T-T_b)} = \frac{70.87*708.33*2345.1*1000*\left(\frac{1.5}{1000}\right)^2*(1-\frac{8.424}{70.87})^2}{100*2*0.163125*(433.15-338.25)} = 66.424\text{s}$$

$$\% \ error = \frac{|t_{exp} - t_m|}{t_m} * 100 = \frac{|73-66.424|}{66.424} * 100 = 9.9\% \ (17)$$

The boiling temperature of water (T_b) is 65,1˚C [17] at 250 mm bar-pressure and the heat of vaporization (ʎ) at this temperature is 2345,1 kJ/kg [18].

Experimental times or work times set in the dryer (t_{exp}) are compared with modelling times (t_m) and error between them is calculated by Formula 15. The following table shows the experimental times, the modelling times, and the errors of a measurement session for the m-log from 1.5 mm veneers.

Table 12. Comparative table between experimental and modelled times for 1,5 mm thickness (I)

Veneer	t_{exp}	t_m	% error
m1	73	66,424	9,901
m2	73	57,601	26,733
m3	93	79,264	17,329
m4	93	78,719	18,142
m5	113	82,239	37,404
m6	53	45,389	16,768
m7	53	49,530	7,006
m8	33	32,854	0,443
m9	33	25,949	27,174
m10	33	26,046	26,699
m11	10	7,970	25,469
m12	10	8,489	17,806

Table 13. Comparative table between experimental and modelled times for 1,5 mm thickness (II)

Veneer	t_{exp}	t_m	% error
m13	30	25,886	15,893
m14	30	20,549	45,994
m15	30	29,775	0,756
m16	30	23,230	29,141
m17	30	19,508	53,784
m18	10	8,983	11,320
m19	50	52,754	5,221
m20	50	54,850	8,843
m21	50	48,272	3,579
m22	70	76,661	8,689
m23	70	68,884	1,620
m24	70	71,217	1,709
m25	110	105,872	3,899
m26	110	105,754	4,015
m27	110	106,242	3,537
m28	110	109,939	0,056
m30	90	94,431	4,692
m31	90	75,783	18,760
m32	90	79,396	13,356
m33	10	5,415	84,663
m34	10	4,966	101,376

The average error of the presented results is 19,75%, underestimating less drying time than the real. However, this error is not very high considering all variable conditions, during drying process, such as temperature of the hot plate, vacuum pressure, and heat conductivity of veneers. Besides, the size of veneers is an approximated value since the cut process is manual.

The model considers no mass transfer resistance, a fact that has increased the error, calculating less required time than the real, as it is shown in Table 11 and Table 12 for most of the modelled times. Even though the initial shock is not contemplated.

This model is also used to calculate the drying time for different thickness. As it is shown bellows, it is more accurate depending on the thickness. The reasons of this fact are analysed, and the models are compared between each other.

The following table is based on 1mm thickness and the work conditions of 250 mbar and 160°C, modelled time is compared with experimental time until 50 seconds, where a moisture-content average of 6% is reached. In this case, the average error is similar to 1,5 mm thickness, being 17,29%.

Table 14. Comparative table between experimental and modelled times for 1 mm thickness, 250 mbar and 160°C

Veneer	t_{exp}	t_m	% error
d1	50	39,531	26,483
d2	50	42,070	18,851
d3	50	43,645	14,560
d4	50	41,675	19,977
d5	50	40,472	23,541
d6	50	41,873	19,409
d7	30	27,709	8,270
d8	30	27,954	7,319
d9	30	27,154	10,480
d10	30	29,177	2,822
d11	30	30,938	3,031
d12	10	9,121	9,637
d13	10	7,127	40,314
d14	10	7,836	27,623
d15	10	7,581	31,907
d16	10	8,895	12,422

The modelled time working at atmospheric pressure is even closer to the experimental one. This fact makes sense since a drying time working under pressure is more difficult to predict because the conditions into the drying box are more variable. Table 15 and Table 16 (same table divided in two parts) show the comparison between modelled and experimental time in this scenario. Both times are very similar, being the average error 12.73%.

Table 15. Comparative table between experimental and modelled times for 1 mm thickness, 1bar and 160°C (I)

Veneer	t_{exp}	t_m	% error
b1	50	44,720	11,807
b2	20	19,055	4,958
b3	50	44,462	12,455
b4	50	44,972	11,180
b5	50	42,889	16,580
b6	50	42,800	16,823
b7	50	46,706	7,052
b8	70	63,458	10,309
b9	70	59,572	17,505

Table 16. Comparative table between experimental and modelled times for 1 mm thickness, 1bar and 160°C (II)

Veneer	t_{exp}	t_m	% error
b10	70	58,345	19,977
b11	70	55,911	25,199
b12	70	60,236	16,209
b13	70	59,852	16,954
b14	30	32,162	3,080
b15	30	31,442	0,863

The modelling for 0.6 mm thickness is the worst case in terms of error. As it is shown in Table 17, the obtained times are around half of the experimental ones, or even lower. This is probably because thickness has non-proportional and non-mathematical relation in drying. Therefore, the model can work properly for some thickness, such as 1 mm and 1,5 mm, and not for others. Moreover, the model assumes that drying conditions are stabilized during the process, but it really takes some time to reach stabilized conditions. As drying time is shorter for these thinner veneers, averages of drying conditions have not been the same as the fixed values in the model.

Table 17. Comparative table between experimental and modelled times for 0.6 mm thickness, 250 mbar and 160°C

Veneer	t_{exp}	t_m
i1	20	11,1913227
i2	10	5,9187822
i3	10	5,0259599
i4	10	6,02286127
i5	10	5,7248729
i6	30	15,2575564
i7	30	15,1613192
i8	30	14,0974592
i9	30	14,6340088
i10	30	14,1441863
i11	30	13,4209214
i12	20	9,16791052
i13	20	9,74993043
i14	20	9,91298854
i15	40	14,7186832
i16	40	14,3715391
i17	40	14,3751548

The last modelling scenario is based on veneers of 3 mm thickness. For these veneers, the modelled time is higher than experimental time, the opposite fact as it happens for the rest of the thickness, although the values are very close for 1 mm and 1,5 mm thickness. Thus, the model works properly for 1 mm and 1,5 mm, but it calculates higher times than reals in case of higher thickness, and the opposite way for lower thickness, where much lower modelled times are reached than the experimental values.

Since there are a lot of data for veneers of 3 mm thickness, modelled times related to the experimental values showed in Figure 26 have been chosen as an example, although the average error is quite similar for the rest of data based on this thickness.

In the following table, there are different veneer letters because they were analysed in the lab at different times, and they were put together depending on their initial moisture content, as it is explained at page 26. The average error in this example is 34,721%. The error probably increases because the model does not consider the mass transfer resistance, and this fact can play a bigger role in case of thicker veneers.

Table 18. Comparative table between experimental and modelled times for 3 mm thickness, 250 mbar and 160°C

Veneer	t_{exp}	t_m	% error
o1	10	10,995	9,050
o2	10	17,269	42,092
o5	10	21,988	54,521
o6	50	91,434	45,316
o7	50	90,848	44,963
o8	50	65,850	24,070
o13	110	188,289	41,579
o14	200	281,260	28,891
o16	200	303,822	34,172
o17	200	313,733	36,251
s5	300	608,851	50,727
s7	20	18,369	8,879
s9	300	544,451	44,899
s10	300	456,400	34,268
s11	300	364,850	17,774
s12	350	570,815	38,684
s13	350	597,239	41,397
s17	400	701,544	42,983
s18	450	734,375	38,723
s19	450	736,221	38,877
v1	110	148,648	25,999
v2	110	160,812	31,597
v3	350	453,737	22,863
v11	10	10,995	9,050

8 Experimental study of electric energy consumption

The aim of this point is to analyse the behaviour of the dryer, and thus, to obtain what happens when the device is drying a veneer. The study plan focusses on measuring the dryer parameters (hot-plate temperatures, drying time and power) and then, analysing them to get the energy amount that goes to dry a veneer (taking the water out), and the energy amount used to increase the hot-plate temperature.

Six spruce veneers of 3 mm thickness were drying, three in moist conditions and three with very low moisture contents (dried veneers).

The average of hot-plate temperatures when the device is drying a moist veneer is lower than the temperatures average "drying" a dried veneer. Therefore, it seems that a part of the total consumption goes to dry veneers or taking the water out, and the other part to heat up the plate.

Theoretically, the total energy goes into taking water out of veneer ($\dot{Q}_{water}$), heating the plate and veneer (E_{plate}), losses of the system, and the mechanical pressure, although for the calculations, energy for mechanical pressure and losses have been considered as negligible. Probably, these assumptions are not very accurate, but it was the only way found to get an energy analysis.

The energy (E_1) to dry a moist veneer is calculated with Formula 19, which has the terms of taking water out and heating plate-veneer, and it is assumed as Formula 20 to the case of "drying" a dried veneer (E_2), where the term of taking water out is removed.

$$E_{plate} = m * Cp * \Delta T \quad (18)$$

$$E_1 = E_{plate\_M} + \dot{Q}_{water} = m * Cp * \Delta T_m + \dot{Q}_{water} \quad (19)$$

$$E_2 = E_{plate\_D} = m * Cp * \Delta T_d \quad (20)$$

Values of the measurements are presented in Table 19 and Table 20 (same table divided in two parts). The parameter called ΔT_{av} represents the average of temperature differential in the hot plate before and after drying veneers 200 seconds. The parameters of m_o and m_1 represent the masses before and after drying, respectively, and dm is the difference between them.

Table 19. Tabulated values required for the energetic study (I)

Veneer	*t(s)*	*ΔT_{av} (°C)*	*m_o(kg)*	*m_1(kg)*	*dm(kg)*
Moist 1	200	9	1381,6	1151,8	229,8
Dry 1	200	16,67	0	0	
Moist 1	200	2,33	1660	1210,4	449,6
Dry 1	200	17,33	0	0	
Moist 1	200	11	1224,4	880,6	343,8
Dry 1	200	33	0	0	
AVERAGE					341,067

A device connected to the dryer, when full heating plate is on, measures a power of approximately 30 kW for all the cases. Therefore, total energy of the system (E) is assumed as equal for all veneers. It is calculated with Formula 21.

$$E = P * t = E_1 = E_2 \ (21)$$

Then, $m * Cp$ is calculated using Formula 20, since ΔT_d is known.

$$m * Cp = \frac{E_2}{\Delta T_d} \ (20)$$

With $m * Cp$ and assuming this value equal for every case, E_{plate} for the case of moist veneers can be calculated as:

$$E_{plate\_M} = m * Cp * \Delta T_m \ (22)$$

Now, $\dot{Q}_{water}$ can be calculated using Formula 19 as:

$$\dot{Q}_{water} = E_1 - E_{plate\_M} \ (19)$$

Calculations of Moist veneer 1 are shown below as an example to explain better the plan.

$$E = P * t = 30\ (kW) * 200\ (s) = 6000\ kJ \ (21)$$

$$m * Cp = \frac{E_2}{\Delta T_d} = \frac{6000}{16.67} = 360\ {}^{kJ}/{}_{\circ C} \ (20)$$

$$Average\ of\ m * Cp = 295.991\ {}^{kJ}/{}_{\circ C}$$

$$E_{plate\_M} = m * Cp * \Delta T_m = 295.991 * 9 = 2663.916\ kJ \ (22)$$

$$\dot{Q}_{water} = E_1 - E_{plate} = 6000 - 2663.916 = 3336.084\ kJ \ (19)$$

Table 20. Tabulated values required for the energetic study (II)

Veneer	*P(kW)*	*E(kJ)*	*$E_2/\Delta T_{av}$ or $m*Cp$*	*E_{plate_M} (kJ)*	*$\dot{Q}_{water}$ (kJ)*
Moist 1	30	6000		2663,916	3336,084
Dry 1	30	6000	360		
Moist 2	30	6000		690,645	5309,355
Dry 2	30	6000	346,154		
Moist 3	30	6000		3255,897	2744,103
Dry 3	30	6000	181,818		
AVERAGE	30	6000	295,991	2203,486	3796,514

The average of $\dot{Q}_{water}$ is divided into the average of *dm* (from Table 18) to get the amount of energy necessary to remove 1 gram of water from a veneer, as it is shown in Formula 23.

$$\epsilon = \frac{\dot{Q}_{water}}{dm} = \frac{3796.514}{341.067} = 11,1313\ {}^{kJ}/{}_{g} \ (23)$$

This is a useful value which represents the required energy (ϵ) to dry a veneer 200 seconds, although this amount of energy is not the same for any drying time because ϵ increase with time, as it is explained in page 39.

Proportion of energy, that use the dryer, to heat up the plate and taking the water out can be calculated with Formula 24 and Formula 25 assuming that they are similar for any drying.

$$\text{п}\ (Heating\ the\ plate)\% = \frac{E_{plate}}{E} * 100 = \frac{2203.486}{6000} * 100 = 36.725\%\ (24)$$

$$\text{т}\ (Taking\ the\ water\ out)\% = \frac{\dot{Q}_{water}}{E} * 100 = \frac{3796.514}{6000} * 100 = 63.275\%\ (25)$$

Using the value obtained in Formula 25, $\dot{Q}_{water}$ can be calculated for different drying times from the total energy used during their process (Formula 26). Then, ϵ could be calculated with Formula 21.

$$\dot{Q}_{water\ i}(kJ) = \frac{\text{т}}{100} * E_i = \frac{\text{т}}{100} * P * t_i = \frac{63.275}{100} * 30(kW) * t_i(s)\ (26)$$

These calculations are done and presented in Table 21 and Table 22 (same table divided in two parts) for a couple of veneers to compare the required energy (ϵ) in different cases (different drying times). The veneers came from spruce veneers of 3 mm thickness and similar moisture content to compare values properly.

Velocity of removing water (v) is also presented, a value that helps to understand the behaviour of veneers when they are drying. This parameter is calculated by Formula 27.

$$\text{v} = \frac{dm}{t} = \frac{m_o - m_1}{t_1}\ (27)$$

Table 21. Table used to calculate the energy necessary to remove mass of water for spruce veneers of 3 mm thickness (I)

Veneer	*m_o(kg)*	*m_1(kg)*	*m_2(kg)*	*dm*	*H_1%*	*H_2%*
o1	2001,50	1852,00	856,00	149,50	133,82	116,36
o2	1986,10	1800,00	852,00	186,10	133,11	111,27
v11	1560,00	1091,10	651,00	468,90	139,63	67,60
o13	1798,00	1235,00	808,90	563,00	122,28	52,68
s7	1387,00	780,50	596,70	606,50	132,45	30,80
s9	1377,80	765,20	599,40	612,60	129,86	27,66
s13	1413,30	658,30	612,70	755,00	130,67	7,44
s14	1780,70	957,80	758,60	822,90	134,74	26,26
X1	1337,60	618,60	574,50	719,00	132,83	7,68

Table 22. Table used to calculate the energy necessary to remove mass of water for spruce veneers of 3 mm thickness (II)

Veneer	$t_1(s)$	$\dot{Q}_{water}$ *(kJ)*	ϵ *(kJ/g)*	*v(g/s)*
o1	10	189,83	1,27	14,95
o2	10	189,83	1,02	18,61
v11	110	2088,08	4,45	4,26
o13	110	2088,08	3,71	5,12
s7	200	3796,51	6,26	3,03
s9	200	3796,51	6,20	3,06
s13	300	5694,77	7,54	2,52
s14	300	5694,77	6,92	2,74
X1	350	6643,90	9,24	2,05

As it is shown in Table 22, the velocity (v) of removing water is much higher for 10 seconds (blue-highlighted value) than 350 seconds (green-highlighted value), and the opposite way for the energy (ϵ), which is higher in the cases of the dryer achieves lower final moisture contents ($H_2\%$) or longer drying times. Therefore, more time reaches more dried veneer, and more dried veneer has more "resistance" to be dried. For this reason, energy increases with drying time.

Moreover, moisture content decreases slower when veneer has lower initial moisture content. Thus, the dryer takes more water out of a veneer of 130% initial moisture content than a veneer of 95%, drying both veneers the same time.

The following table shows some examples of this fact, where two veneers of 133% initial moisture content dried 10 seconds are compared to two veneers of 91.94% and 98.65% also dried the same time. The differences in removed water (*dm*) or removed moisture content (*dH*) are notable, being *dH* three times higher for the moistest veneers (blue-highlighted values).

Table 23. Comparative table of removed water and removed moisture content for spruce veneers of 3mm thickness and different initial moisture contents.

Veneer	$m_o(kg)$	$m_1(kg)$	$m_2(kg)$	*dm(mo-m1)*	H_1 *%*	H_2 *%*	*dH*
o1	2001,5	1852	856,0	149,5	133,82	116,355	17,46
o2	1986,1	1800	852,0	186,1	133,11	111,268	21,84
n31	1905,6	1845,2	992,8	60,4	91,94	85,86	6,08
n32	1881,2	1820,0	947,0	61,2	98,65	92,19	6,46

9 Conclusions

The main goal of this thesis, which was defining drying times required to dry different thickness at specific drying conditions, has been reached. After all the presented drying curves, the reader can get a proper estimation of required time and knowledge about veneers behaviour depending on their thickness and the conditions in which they are dried.

The differences in drying times are higher between thicker veneers. Comparing with 1,5mm thickness, if we want to dry a 0,75 mm thickness veneer, we know that will be less than half of time required for 1,5 mm, and the other way for thicker veneers, where more than double will be for 3 mm thickness veneers.

The curves of 1,5 mm have a close relation between moisture content and drying time, being their slope close to one. In this way, working with less thickness than 1,5 mm, we can assume that less drying time in seconds than initial moisture content in percentage will be enough to get a dried veneer, and also the opposite way for higher thickness.

The drying times studied for the measured thickness are, therefore, useful not only for these thicknesses but it can be properly used for a huge range of thickness taking as reference 1,5 mm thickness.

The initial heat shock increases with temperature but decreases with thickness. The bigger shocks can be achieved with high temperature and low thickness. Then, a 0,6mm thickness veneer can be quickly dried if the temperature of the hot plate will be 200◦C, for example, since more than half of initial moisture content is already dried in the case of 160◦C.

The positive vacuum effect in drying process has been also demonstrated. Working with vacuum pressure, the dryer can reach low moisture contents (5%) around 20 seconds before working at atmospheric conditions.

The variation of the working parameters as hot-plate temperature and drying pressure has been continuous during all measurement sessions. However, the proposed modelled drying time seems like decently work for a couple of thickness, and it can take as the starting point for future research where drying parameters would be analysed more deeply. In this point, interesting estimated values have been achieved for 1,5 mm and 1 mm thickness. If the modelled values would be set in the dryer, very similar final moisture content would be reached, that is the most important in fact.

Interesting facts can be also concluded from the energy consumption study. The energy amount necessary for the drying process increases as veneer is losing water. Thus, more energy will be necessary to dry a veneer from 50% to 40% than the same veneer from 90% to 80%, for example. Then, it can be concluded as veneers take “resistance” to be dried when they are losing their water.

10 References

[1] Ministry of Agriculture and Forestry & Finnish Forest Research Institute (Metla) (2012). State of Finland´s Forests 2012 based on the Criteria and Indicators of Sustainable Forest Management [online journal] Criterion 6 Socio-economics functions [Cited 4 February 2020] Available at: http://www.metla.fi/metinfo/sustainability/c6.htm

[2] Suorsa Jarmo (2019). Forest Industry. Finnish Forest Industries Federation. [online material] [Cited 4 February 2020] Availabe at: https://www.forestindustries.fi/statistics/forest-industry/

[3] Martin P Ansell (2015) Wood Composites. Woodhead Publishing. p 69-86. ISBN 978-1-78242-454-3

[4] Finnish Forest Industries Federation (2002). Handbook of Finnish Plywood. p 5-26. ISBN 952-9506-63-5

[5] Prentice Hall, Englewood Cliffs, NJ (1990). Wood Engineering Handbook, Second edition; Forest Products Laboratory. [online material] matweb.com [Cited 1 June 2020] Available at: http://www.matweb.com/search/GetReference.aspx?matid=71376

[6] John F. Lutz (1974) Techniques for Peeling, Slicing and Drying Veneer. USDA Forest Service Research Paper FPL 228. p 41-43.

[7] Science Facts (2020). Part of a Tree Trunk. [online material] ScienceFacts.net [Cited 1 June 2020] Availabe at: https://www.sciencefacts.net/parts-of-a-tree.html

[8] Ms. Aye Aye Thant, Dr.San SanYee, Dr.Than Than Htike (2009). Modelling Drying Time during Veneer Drying and Comparison with Experimental Study. Proceedings of the International Multiconference of Engineers and Computer Scientists 2009 Vol II IMECS 2009. ISBN: 978-988-17012-7-5

[9] O Paajanen, H Holmberg, P Lahti & M Kairi (2012) Experiences with new veneer drying method, International Wood Products Journal, 3:1, 26-30, DOI: 10.1179/2042645312Y.0000000011

[10] H Holmberg (2008). Selecting a dryer – A new drying method. Aalto University material.

[11] BSY Industry Group (2015). Mess-roller Combined Dryer BG 1933 [online material] bsywoodworking.com [Cited 15 March 2020] Available at: http://www.bsywoodworking.com/Mess-roller-Combined-Veneer-Dryer-BG1933-29.html

[12] HANVY Machinery (2016). Veneer Roller Dryer [online material] hanvymachinery.com [Cited 16 March 2020] Available at: http://www.hanvymachinery.com/plywood-machine/veneer-dryers/veneer-roller-dryer.html

[13] SHANDONG YUEQUN Machinery (2020). Hot Press Machine [online material] yuequnmachinery.com [Cited 18 March 2020] Available at: https://www.yuequnmachinery.com/linyi-15-layers-500t-hot-plate-hydraulic-hot-press-plywood-machine.html

[14] WUXI HAOXIANG Machinery (2020). HDG-Z Longitudinal Veneer Hot-pressing Dryer [online material] wxhxjx.cn [Cited 18 March 2020] Available at: http://www.wxhxjx.cn/en/product_64

[15] SHANDONG GEELONG Machinery Technology (202). Plywood Machine 15 Layers Hot Press Veneer Dryer Machine [online material] wxhxjx.cn [Cited 18 March 2020] Available at: https://geelongmachinery.en.made-in-china.com/print/TyPQwDLEnFkN/China-Plywood-Machine-15-Layers-Hot-Press-Veneer-Dryer-Machine.html

[16] Franz F.P. Kollman & Wilfred A. Cote (1968). Principles of Wood science and Technology. DOI: 10.1007/978-3-642-87928-9

[17] Glass, Samuel & Zelinka, Samuel. (2010). Moisture relations and physical properties of wood. Wood handbook: wood as an engineering material: chapter 4. Centennial ed. General technical report FPL; GTR-190. Madison, WI: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory. p. 4.1-4.19.

[18] The Engineering Toolbox (2020). Online Water Heat of Vaporization Calculator. Available at: https://www.engineeringtoolbox.com/water-properties-d_1573.html